

FRYING AND REHEATING IN A

FORCED CONVECTION OVEN

CHRISTINA SKJÖLDEBRAND

CIV.ING., VRML

Lund 1979

AVHANDLING FÖR TEKNISK DOKTORSEXAMEN



**DIVISION
OF
FOOD ENGINEERING**

AVDELNINGEN FÖR LIVSMEDELSTEKNIK

**LUND INSTITUTE OF TECHNOLOGY
LUND - SWEDEN**





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Abstract
The frying and reheating process of minced meat products in a forced convection oven has been studied. The influence of air parameters, such as temperature, velocity and humidity, on product quality was estimated in order to optimize the process.

A research convection oven was designed and built.

The research programme was divided into two parts ending at the same overall goal.

In the first part, the directly analysed quality changes were examined. The process time, weight losses, crust colour, thiamine retention and sensorial properties were measured.

In the second part, heat and mass transfer both between air and product and within the product as well as crust formation were studied. For example, the thermal conductivity, the moisture content of the crust and the heat and mass transfer coefficients were calculated.

The product used was minced meat loaves with the dimensions 200x50x50 mm. The conclusions from the investigation were that:

To minimize weight losses during frying and reheating of minced meat loaves air temperatures below 200°C should be used.

At these temperatures high air velocities should be used.

To produce a proper crust at these temperatures the air should be dry at least at the end of the process.

When reheating a precooked product, the humidity of the air should be high to minimize weight losses.

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FRYING AND REHEATING IN A FORCED CONVECTION OVEN.

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This thesis is based on the following papers:

(referred to in the text by their numbers).

1. C. Skjöldebrand (1976); Konvektionsugnar. Livsmedelsteknik 8, 364-366. (translated into English).
2. C. Skjöldebrand and R. Öste (1977); Quality changes during heating of meat products in convection oven; How Ready are Ready-to-serve Foods? (Editor K. Paulus, Karlsruhe), S. Karger Verlag, Basel, 236-246.
3. C. Skjöldebrand and R. Öste; Some aspects on frying of meat products in a forced convection oven. Accepted for publication in Lebensmittel-Wissenschaft und Technologie.
4. C. Skjöldebrand and R. Öste (1979); Reheating of meat products in a convection oven. Contribution at Symposium of Catering System Design '79 in Harrogate 10-13th September 1979.
5. C. Skjöldebrand; Convection oven frying I: Heat and mass transfer between air and product. Submitted for publication to J. Food Science.
6. C. Skjöldebrand and B. Hallström; Convection oven frying II: Heat and mass transfer in the product. Submitted for publication to J. Food Science.
7. C. Skjöldebrand and H. Olsson; Crust formation during frying of minced meat products. Submitted for publication in Lebensmittel- - Wissenschaft u. Technologie

1. INTRODUCTION

1.1. Background

The volume of ready-to-serve food prepared in the food industry and catering establishments has grown enormously in the industrial world during recent years. In Sweden with 8 million inhabitants about 4.7 million meals are served outside the home everyday. The development however of preparation processes have not progressed concurrently. Problems in getting a good tasting and nutritious meal arose when the methods used in households were enlarged. Fundamental theories have to be developed for these traditional methods and new processes have to be introduced. In catering establishments many meals have to be served within a very short time which gives rise to new problems such as how to reheat precooked food or to keep meals warm for a long time. The procedure for these processes have also to be methodically examined to see what effect they have on the change in quality of the food produced.

Four different essential methods are used for frying food products. These are convection via fat such as deep-fat frying, conduction via a hot surface, for example, pan frying, convection via air in a convection oven and infra-red radiation in an infra-red radiation oven.

During the last few years som results have been presented in the literature where these frying operations have been investigated. Godsalve et al., (1977) and Hung et al., (1978) have studied the cooking of bovine muscles in dry air. Dagerskog, (1978) examined the fundamental process involved in contact frying and carried out some research on frying with infra-red radiation. Temperature measurement techniques and the physical phenomena taking place in deep-fat frying were studied by Sörenfors, (1978) and a mathematical model was derived for the frying process. A comparison of the four different methods has been made by Dagerskog and Sörenfors, (1978) by frying the same product (meat patties).

Warmholding of food products in catering establishments has also been examined during recent years (Hansson et al., 1972; Karlström and Jonsson, 1976).

This project deals with problems concerning frying and reheating in forced convection ovens.

1.2. Purpose and extent of the work.

The convection oven is one of the most useful devices in catering establishments. The reason for this is that it has many applications and can be used for frying, boiling, reheating, thawing and warm-holding of food of many geometries and types.

Convection means that heat transport occurs with the aid of a flowing gas or liquid. The product being heated is subjected to the higher temperature of the gas or liquid.

A commercial convection oven consists of an oven compartment in which heated gas, often air is circulated by a fan. Very few ovens, however, allow variation of air velocity. Sometimes a steam generator is connected to the oven to give a mixture of steam and air in the oven cavity. The size of these ovens varies from large continuous ovens for industrial use to small cupboards for heating single packages in catering.

Some studies have been carried out on commercial convection ovens to examine reheating of packages of frozen, precooked food (Co et al., 1968; Walker et al., 1969; Dorney et al., 1971; Paulus, 1974 and Housova, 1972). Quality changes during frying in existing convection ovens have been studied by McCommon et al., (1970), Bengtsson et al., (1976) and Funk et al., (1966). Earlier application of the convection ovens also includes baking. Mathematical models have been formulated in Eastern Europe to estimate heat and mass transfer in baking (Tichy, 1974; Housova, 1977).

Before the present research work was started some representatives from catering and industry were interviewed about the use of convection ovens so as to obtain information as a preparation for the research programme (Tillman, 1975). The report came to the conclusion that convection ovens are mostly used for frying and consequently we developed an oven suited for this need.

The purpose of this project was to examine the frying and reheating operation in convection ovens so as to make recommendations to operators in the catering establishments on how to use them and to the manufacturers on how to make them. The research programme can be divided into two parts (see figure 1) ending at the same overall goal, i.e. optimizing the process starting from the properties of the food, by manipulation of the air parameters; temperature, velocity and humidity.

In the first part, reported in papers 2, 3 and 4, the directly analysed quality changes when frying or reheating food were examined. The process time, weight losses, crust colour, thiamine retention and sensorial properties at different temperatures, velocities and humidities were studied.

The physical properties and their changes during frying have to be known in order to optimize the process and predict quality changes. Heat and mass transfer both between air and product and within the product are the basis for these phenomena. Papers 5 and 6 deal with these problems.

In connection with the convection oven research programme a project has been started in Sweden in which the formation of the crust especially on minced meat products is being studied. The aim is to explain physical and chemical properties of the crust, to know its nutritional value and its role in the frying process. The conditions for making an acceptable or proper crust are to be studied. The different methods of frying will be examined and the first results from this work is reported in paper 7.

2. RESEARCH CONVECTION OVEN.

A research convection oven was designed and built. The purpose was to have a device where the air conditions, i.e. air flow, air temperature and air humidity, could be precisely known. The air velocity should be as uniform as possible when it reaches the product and it should be possible to reverse the air. Figure 2 shows the principle of this oven and Figure 3 a photograph of it.

The oven was built like a wind tunnel with a centrifugal fan to regulate the air flow through the oven cavity.

The air stream was dispersed by guide plates and finely meshed netting to obtain the uniform air stream needed. The oven cavity which had the dimensions 325 x 325 x 325 mm, had three net shelves. The shelves of the oven compartment were attached to a door in front and a wall behind and this arrangement was mounted on wheels. This enabled the oven compartment to be pulled out without disturbing the air system. In this way the product being fried could be prepared and placed on the nets and the oven could be pushed back into the air stream without disturbing the balance. A glass window is placed on the top roof so that the product can be seen during the whole procedure.

In the oven cavity there was equipment for measuring air humidity and air velocity, a thermocouple measured and regulated the air temperature and this temperature could be varied between 20°C and 400°C. A maximum power of 15kW was supplied for heating the air. A special unit was designed to measure the air humidity (Sörenfors and Ånäs, 1977) and this consisted of a glass bowl filled to three-quarters full with water. The water boiled slowly and one of two thermocouples in the unit was continuously wetted by means of a wick (figure 4). Moist air from the oven was cooled to 100°C and passed the thermocouples. The dry and wet temperatures were measured. The humidity could be varied between dry air and pure steam.

The air velocity could be varied continuously between 2-12 m/s and was measured by means of a Prandtl tube. The stream of air could be reversed with intervals from between 3 seconds up to 30 minutes. During frying two different time intervals could be chosen, shorter at the start than at the end.

The temperature of the product was measured by means of thermocouples which ran through holes in the oven door. Chromel-alumel thermocouples with a total diameter of 0.5 mm were used (thread diameter, 0.12 mm) according to investigations made at the institute. The error in temperature measurement by this method was one third of the error when measuring with copper constantan (Sörenfors, 1978). The surface temperature was measured by means of an IR-sensing head (Raytek Thermalert LC 814) since the infrared radiation is a function of the temperature on the surface (Mahnke et al., 1973). This sensing head was a so called partial radiating pyrometer, which means that only wavelengths between 8 and 14 microns were monitored; water in the air did not disturb the measurements.

It was possible to weigh continuously the product being heated by means of a balance and in this way the moisture loss rate could be measured during frying. The balance consisted of strain gauges held on a frame that was placed outside the glass window on the roof as the oven. The product was hung on a wire coupled to the strain gauge.

All temperature, humidity, velocity and weighing values passed through a data logger and were registered on a punched tape for further computer evaluation.

3. SPECIAL MEASUREMENTS PROBLEMS.

To avoid temperature measurement errors the following recommendations (Sörenfors, 1978) were followed for all experiments a) chromel-alumel thermocouples were used, b) the thermocouples were sewed into the product from its short side and c) a thermocouple thread with minimum diameter was chosen (5).

The infra-red radiation is proportional to the surface temperature and the proportionality depends on the product.

The change in brightness of the product during frying causes deviations from proportionality (5).

Problems arose when continuously weighing the product during frying because air flow disturbed the balance. As a result many peaks were found on the weighing curve and this had to be integrated (5).

4. THEORY

To be able to optimize the frying operation the mechanisms for heat and mass transfer had to be investigated. Frying and reheating in a convection oven is a drying operation at high air temperatures. The distinction from, for example, frying of vegetables is that only the surface should be dried. Many food products are characterized by their porosity. Several textbooks present theories for the fundamental drying mechanisms in this type of materials (Krischer, 1963; Keey, 1972; Lykow, 1955; Kneule, 1975). Physical phenomena in drying of foodstuffs have been studied among others by Görling, (1956); Karel, (1975) and Bruin, (1979).

When a product is dried or fried in a convection oven, an exchange of heat and water between air and product takes place. In determining the transfer conditions three stages of the process can be separated. These are discussed in publication 5 and are presented briefly here.

- a) Preheating of the product surface from initial temperature to the dew point.
- b) Constant surface temperature (equal to the wet bulb temperature): this is the constant rate period using drying terminology.
- c) The surface temperature increases above the wet bulb temperature and this is the so called falling rate period.

In drying processes a fundamental characteristic of the food material is its sorption isotherm. This is a relationship between the amount of water held in the product after equilibrium at a constant temperature and the relative humidity

of the space surrounding the material (Labuza, 1968). The sorption isotherm changes when the temperature changes as a result of chemical changes. In frying a crust is formed on the surface of the product. The crust is defined as the part of the product having reached a temperature above 100°C . Due to the Maillard reactions and other chemical reactions the equilibrium water content is low, lower than the parts inside the crust. Most of the water is assumed to evaporate in a zone where the temperature is 100°C . To be able to calculate the moisture content and the temperature profile in the crust some assumptions were made (5):

- a) All transports of water in the crust take place as vapour i.e. the flow of vapour is proportional to the vapour pressure drop in the crust.
- b) In this transport the mass of vapour refers only to the changed position of the 100°C isotherm.
- c) The partial vapour pressure in the crust is at any moment supposed to be in equilibrium with the water content of the crust at actual temperature (Harmathy, 1969).
- d) In the crust the product properties are changed because of heat denaturation.
- e) From the flow of heat the thermal conductivity of the crust is calculated.
- f) Shrinkage is neglected.

It is known that heating of meat influences the structure of the proteins in meat and this has been studied in many investigations (Hamm, 1977). Hamm et al., (1960) examined the relation between temperature, pH and bonded water for meat muscles. It was found that protein denaturation had already started at 30°C and ended at about 65°C . This is signified by an increase in so called water holding capacity (WHC). This means that as the protein changes water is pressed out of the product and this gives the so called "drip" losses in distinction from evaporation losses. Dagerskog, (1978) has also studied the water holding capacity of minced meat as a function of temperature.

5. PRODUCT

Throughout this research work minced meat products made into loaves were used. Minced meat products are very common in Sweden and Swedish food law gives the minimum amount of meat that must be used as a ingredient; potato starch and bread crumbs are often found in these recipes. Three different recipes were used in this project and the different ingredients used give different physical and chemical properties to the product. In publications 2,3,4,5 and 6 an industrial recipe (recipe A) was used. In addition to the industrial recipe one consisting of meat and water only (recipe B) was used and the water holding capacity compared to that of recipe A (6). For the experiments reported in publication 7 a special recipe was designed with properties similar to the industrial one (recipe C). The composition of these recipes are given in Table 1.

Table 1. Composition of minced meat recipes.

	Water %	Fat %	Fat Free Dry Substance (FFDS) %
Recipe A	63	13.1	23.9
Recipe B	65	19.1	15.9
Recipe C	66.3	11.3	22.4

In an investigation reported in the literature a comparison between four different methods of frying meat patties was made (Dagerskog and Sörenfors, 1978). It was found that in convection oven frying, high air temperature and high velocity of air had to be used to reach the proper temperature in the center of the product and at the same time to give an acceptable crust. This is caused by the comparatively low heat transfer coefficients in this type of equipment.

In this project a geometry of the product that required long frying times was chosen. In this way a proper crust formed before the center has reached the required temperature for the ready-made product.

6. FRYING AND REHEATING PROCEDURE

The frying and reheating procedures are described in the publications. In all heating procedures the product was placed in a teflon coated net cage to avoid deformation. The air velocities and air humidities were varied in the same way throughout the investigation.

In publication 7 one combination of air parameters was used, 225°C, 5 m/s (air velocity) and "dry" air. ("Dry" means a humidity very close to 0 kg/kg humid air). This combination has been commonly used in a commercial convection oven. The temperature in the center of the product was measured. In some frying experiments the surface temperature and also the temperature at different distances from the surface except the center were measured (5).

On reheating some loaves were fried at 150°C, 9 m/s and "dry" air for 30 minutes before storing and reheating. This combination had been found most suitable from the frying experiments. A loaf fried under this combination did not lose much water, had an acceptable crust colour and had high sensorial scores. Some loaves were "boiled" at 125°C, 5 m/s and humid air before reheating. The reason for this was to see if it was possible to coagulate the meat with minimum weight losses and to form a crust during reheating. When reheating the pre-fried loaves, lower temperatures were used than when frying and reheating the boiled product. The reason for this was that the loaves had already got an acceptable crust colour and there should be no further formation of crust during reheating.

7. ANALYSIS AND CALCULATIONS

Time, weight losses, colour of the crust, thiamine retention and sensorial properties of the product were analysed to get a direct measure of the quality.

From the literature it is known that thiamine is heat labile and it has been found that there are great losses of this vitamin in the reheating and warmholding processes (Ang et al., (1975): losses up to 75 % have been found (Lang, 1970).

Because of this thiamine was analysed according to the Associations of Vitamin Chemists, (1951) to estimate the nutritional value of the products and the analysis of vitamin is described in publications 2 and 4.

Frying of meat products is among other things characterized by formation of a brown coloured crust. The crust is formed by chemical and structural changes at high temperatures. The brown colour is to a large extent due to the Maillard reactions (Hurrell et al., 1977; Cheftel, 1977). This is a reaction between a reducing sugar and an amino acid and plays an important role in the food processing (Adrian, 1974). The crust colour has been studied in publications 3, 4 and 7.

The sensorial properties are very important for processed foods and have been analysed in the investigations reported in publications 3 and 4.

The time from the start of the process until the center of the product reached $65-70^{\circ}\text{C}$ was estimated. This is a relevant temperature for ready-cooked food. Weight losses during the period were studied.

Water holding capacity was analysed according to the method described by Dagerskog, (1978).

Sorption isotherm measurements are described in publication 6 and were carried out as follows: one sample of meat was fried to 180°C and another was boiled at 100°C and these were measured in a Sina Scope hygrometer at 25°C and at 45°C (Karan-Djurdjic, 1970).

The heat and mass transfer coefficients were calculated as described in publications 5 and 6 for the following periods.

1. The constant rate period.
2. The falling rate period, which was divided into two parts.

The temperature profile in the crust was calculated from the temperature measurements in the product.

The moisture content profile in the crust was determined from the extrapolated sorption isotherms and the calculated partial vapour pressure in the crust at different distances. It was assumed that the water activity in the evaporating zone was equal to 1 ($a_w = \phi = 1$) and less than 1 at any distance outside this zone. The surface partial vapour pressure was calculated in publication 5 from the heat transfer coefficients (Krischer, 1963).

The degree of chemical changes in the crust could be accounted for by knowing the sorption isotherm for two different degrees of denaturation of the product. Knowing the temperature at each point the moisture content could be calculated from a modified Arrhenius equation.

The thermal conductivity of the crust was calculated from the equation (Krischer, 1963; Kneule, 1975).

$$\frac{\lambda}{l_c} (t_s - 100) = \alpha (t_a - t_s)$$

Where α is the calculated mean value of heat transfer coefficient and λ the thermal conductivity (6).

The local λ -values could be calculated assuming the flow of heat to be constant and knowing that the λ -values are proportional to the temperature gradient.

8. RESULTS

8.1. Heat transfer coefficients.

The heat transfer coefficients were calculated during the frying procedure so that the energy supplied at different air parameters could be estimated and these results are shown in figure 5 (5). Four examples of the time/temperature curves

at different distances from the surface of the product are shown in figures 6 and 7 (6). It was found that heat transfer coefficients varied considerably within one frying procedure and between two different air velocities. However, on increasing the air temperature the heat transfer coefficients did not increase. At the lowest air temperature these coefficients increased at the start of frying when the air humidity was raised. It was assumed that there was no deformation of the meat loaf, when the heat transfer properties were calculated, but this was hard to avoid in spite of the net cage in which the loaves were placed.

8.2. Thermal conductivity of the crust.

Sörenfors and Dagerskog, (1978) determined the thermal conductivity of minced meat products and an equation was formulated for the parts inside the crust. Dagerskog, (1978) calculated the thermal conductivity of the crust when the product was pan-fried and he found that at a mean moisture content of 0.25-0.4 kg/kg of fat-free dry substance the conductivity was 0.2-0.3 W/m °C.

From known values of the heat transfer coefficients and the surface temperature the mean "apparent" thermal conductivity of the crust could be determined (6). These are shown at different periods and for different frying procedures in Table 2. At 225°C, 9 m/s and "dry" air the thermal conductivity was found to be 0.24 W/m °C, and the mean moisture content was 0.15 kg/kg of dry substance which is about the same as that found by Dagerskog, (1978).

Table 2. Thermal conductivity of the crust.

λ (W/m °C)	150°C			225°C		
Period	5 m/s dry air	5 m/s humid air	9 m/s dry air	5 m/s dry air	5 m/s humid air	9 m/s dry air
When $t_c = 70^\circ\text{C}$	0.09	-	0.09	0.21	0.16	0.19
After 45 minutes	0.09	-	0.09	0.24	0.08	0.26

As the local value of the thermal conductivity in the crust is proportional to the temperature gradient (the flow of heat is assumed constant) such values could be calculated. As the moisture content also is a function of depth, a diagram of thermal conductivity versus moisture content was plotted (figure 8). It is evident that in the crust the thermal conductivity is strongly dependent on temperature moisture content and structure (porosity). Thus, λ -value of the crust depends not only on moisture content (e.g. Earle, 1969). From the equation formulated by Sörenfors et al., (1978) it was found that for this recipe the thermal conductivity inside the crust at 100°C and at initial moisture content would be $0.62 \text{ W/m } ^\circ\text{C}$. The values calculated in this investigation were $0.5\text{--}0.6 \text{ W/m } ^\circ\text{C}$. In the crust the local thermal conductivity was low and increased towards the evaporation zone and then decreased again towards the center.

8.3 Heating time.

Figure 9 shows the variation of frying time when changing air velocity, air temperature and air humidity (2 and 3). The time was measured from the start of frying until the center of the product reached 70°C . This temperature is considered relevant for a ready-made product. It is evident that only at the lowest air temperature could the heating time be influenced by altering any of the air parameters.

The same results were found when reheating the minced meat loaves after frying and storage (figure 9). For example, on reheating a prefried meat loaf the heating time is reduced by 55 % when the air was humidified at 125°C , 3 m/s and "dry" air. Furthermore, heating time was reduced by 19 % on raising the temperature to 150°C and 40 % on raising it to 200°C . When the air velocity was changed from 3 m/s to 9 m/s at 125°C the heating time is reduced by 32 %. It could be seen from the temperature curves (figures 6 and 7) that the surface temperature rises to 100°C very slowly at 150°C and 5 m/s "dry" air. However, when the air velocity is increased to 9 m/s rise in surface temperature to 150°C is comparatively rapid. A further rise in air temperature increases this period somewhat more.

In table 3 heating times taken from the temperature curves (figures 6 and 7) are summarized.

Table 3. Heating Times for different stages in the frying process.

Air velocity (m/s)	150°C		225°C	
	When $t_s=100^{\circ}\text{C}$ (s)	When $t_c=70^{\circ}\text{C}$ (s)	When $t_s=100^{\circ}\text{C}$ (s)	When $t_c=70^{\circ}\text{C}$ (s)
5	1300	$2400-1300=1100$	350	$1700-350=1350$
9	500	$1800-500=1300$	250	$1600-250=1350$

From these results it can be seen that the period from 100°C on the surface until the center has reached 70°C has almost the same length (1100-1350 s). This depends, however, on what the temperature is in the center when surface is 100°C . The explanation for this could be that the frying procedure could be divided into two periods (Dagerskog, 1978, Sörenfors, 1978) leaving the drying theories out of account. In the first period the surface temperature raises to 100°C and the energy transport depends on the air conditions only. During the second period crust has been formed and the energy transported to the center depends on the temperature gradient inside the crust. The length

of the first period can be influenced by changing air parameters. When the energy transported to the product is above a certain amount this period will be short compared with the second period. The total frying time is then not influenced very much.

8.4 Crust Moisture Content.

Figure 10 shows some examples of moisture content profiles in the crust calculated from the sorption isotherm at different degrees of chemical change (6). These profiles were found to be very steep just outside the 100°C isotherm. The moisture content on the 100°C isotherm is highly dependent on the sorption isotherm and the water holding capacity (WHC). These properties could be changed by the ingredients used in the minced meat product.

8.5 Water holding capacity.

In figure 11 the water holding capacity (WHC) as a function of temperature and time when using different recipes has been shown (6). This property is dependent on the ingredients of the minced meat mixture. The recipe consisting only of water and meat at relatively low temperatures showed a large decrease in the water holding capacity. This is because of the changes in the meat when the protein is denatured. When, for example, potato starch and bread crumbs are added to the recipe these ingredients take up the water expelled from the meat and give rise to the effect shown in figure 11.

8.6 Weight losses and crust colour. (2, 3 and 4).

Figures 12 and 13 illustrate the weight losses and the crust colour when the meat loaves were fried and reheated. Dagerskog and Sörenfors, (1978) found that between 10 % and 15 % brightness in the crust colour was acceptable and these two limits have been drawn in the diagrams. The losses in weight and colour of the product were remarkably influenced when heating was performed above a certain temperature. At 125°C and 150°C, only minor weight losses were observed when reheating a pre-fried meat loaf; in humid air this procedure gave almost zero losses.

The crust colour was almost the same at 125°C and 150°C after reheating the prefried loaves. These results show that since the prefried loaves had already an acceptable crust colour, the energy transported to the surface is used for heating the product and not so much for the evaporation of water. At 200°C, however, a dark product was obtained with relatively high weight losses which indicates that a lot of energy was used to evaporate water in the crust and heat the crust. In publication 4 results are given in which a boiled product was reheated and this procedure gave a dark product with high weight losses. Boiling of minced meat seems to facilitate the browning reaction when the product is later fried. The boiled reheated product was darker and lost more water at the same air parameters compared with the fresh fried meat loaves.

8.7 Thiamine content.

The thiamine content is influenced by heating of the product and accordingly less thiamine was retained at the higher temperatures than at the low. A number of workers e.g. Teixeira et al., (1969), Manson et al., (1970) and Teixeira et al., (1975 a) estimated the nutritional losses for conduction-heated foods by means of a computer programme and in this way the optimal time/temperature relationship could be determined. These computer programmes were set up for sterilization in cans and it was assumed that the surface temperature rises immediately to the surrounding temperature. Teixeira et al., (1975 b) improved the computer programme by varying the surface temperature.

Before the frying and reheating experiments started an investigation was made to estimate thiamine degradation in minced meat. The activation energy and the chemical reaction constant were determined (Sjödén, 1977). From these data and a model for calculating nutrient retention made by Jen et al., (1971) a computer programme was made to calculate mean thiamine content and the local values in the minced meat loaves. Six meat loaves, fried under different air conditions, were analysed for thiamine and temperatures at the surface and inside the product were measured. The temperature changes in the middle part are influenced

only by heat transfer from the large sides because of the shape of the loaf (200 x 50 x 50 mm). The values of the thiamine content from the computer programme were calculated in this middle part and these data have not yet been published. Figures 14 and 15 show some preliminary results from the experimental values compared with the calculated values; this meat loaf was fried at 150°C, 9 m/s and "dry" air. The calculated total thiamine retention was 88.6 % and the experimental value was 87.1 %. This is one way of using the quality properties determined in this project. Further improvements of this model are in progress.

9. CONCLUSIONS

The results obtained in this project show that both frying and reheating of meat loaves of the dimensions (200 x 50 x 50 mm) are possible in a forced convection oven. There are different aims, however, for these two processes. In frying, enough energy must be supplied to the product both to form a crust and heat the product. In reheating, however, the product has been prepared beforehand and the energy supplied is used for heating to a temperature at which the product is palatable. Furthermore, as nutritional and other quality losses have occurred during preparation it is important to avoid any further losses. From the experiments it can be seen that weight losses are increasing with temperature of the air. After frying at any air humidity the product would be too dark at air temperatures above 225°C and when the air velocity is above 5 m/s at 225°C. After reheating, the product was too dark at air temperatures above 150°C. Thus, convection frying or reheating should be performed at low air temperatures which means that the process will be influenced by air velocity or air humidity or both. When frying at low air temperatures the air should be dry to get a proper crust. However, when reheating either a prefried product or a preboiled product humid air could be used.

The frying and the reheating processes could be divided into two parts 1) from the start until the surface reaches 100°C and 2) from the time when the surface has reached 100°C until

the center is 70°C . During the first period the temperatures in the product will be influenced by the parameters only. During the second period the center temperature will be influenced by the temperature gradient inside the crust. As energy transported inside the product does not reach the center immediately this temperature will rise more slowly. This means that at high air temperatures or high air velocities the first period is so short that the center temperature is still unchanged when the second period starts and thus this period will have approximately the same length independent of the air parameters. This leads, also, to the fact that the second period is relatively long compared with the first and the total heating time will not be influenced very much.

At high air humidities, low temperatures and low velocities the surface temperature rises immediately to the wet bulb temperature and the energy transported to the center is faster than at dry air, but it takes a long time before the surface reaches 100°C . When air velocity and air temperature are high this gives enough energy to heat the product and here air humidity gives no further advantage. The surplus energy in the second period is used up in the evaporation of water thus increasing weight losses.

An optimization of the process would give the following results:

- 1) Frying and reheating of meat loaves at air temperatures below 200°C should minimize weight losses.
- 2) At these temperatures high velocities should be used
- 3) To get a proper crust at these temperatures the air should be dry at least at the end of the process.
- 4) Reheating should be performed at high humidities to minimize weight losses.
- 5) To minimize losses and get a proper crust the meat loaves should be prefried and not preboiled before reheating. This conclusion is strengthened by the fact that the sensorial properties are significantly better for the prefried.

In the frying process, the product thickness must be large enough to give a crust during the time of heating to 70°C in the center. As it takes a comparatively long time to reach 100°C on the surface at low air temperatures, the product must be thick enough not to reach 70°C in the center within this first period. The conclusion therefore, is that there is a minimum thickness for the product that is to be fried in a convection oven.

This investigation has given fundamental information about reheating and frying of meat loaves in a convection oven. An indication has been given of the air conditions that can be used for different products. To be able to make a theoretical and general model further investigations have to be performed and a complete computer programme has to be made. The relationship between the chemical and physical changes and consumer notion of quality in the product must be an object for further investigation.

10. ACKNOWLEDGEMENTS.

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I thank Dr. Tadhg Griffin and Elsa Sivik for linguistic advice.

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11. NOMENCLATURE

λ	thermal conductivity of the crust (W/m, °C)
ℓ_c	depth of the crust (m)
t_s	surface temperature (°C)
t_a	air temperature (°C)
t_c	center temperature (°C)
α	heat transfer coefficient (W/m ² , °C)

12. REFERENCES

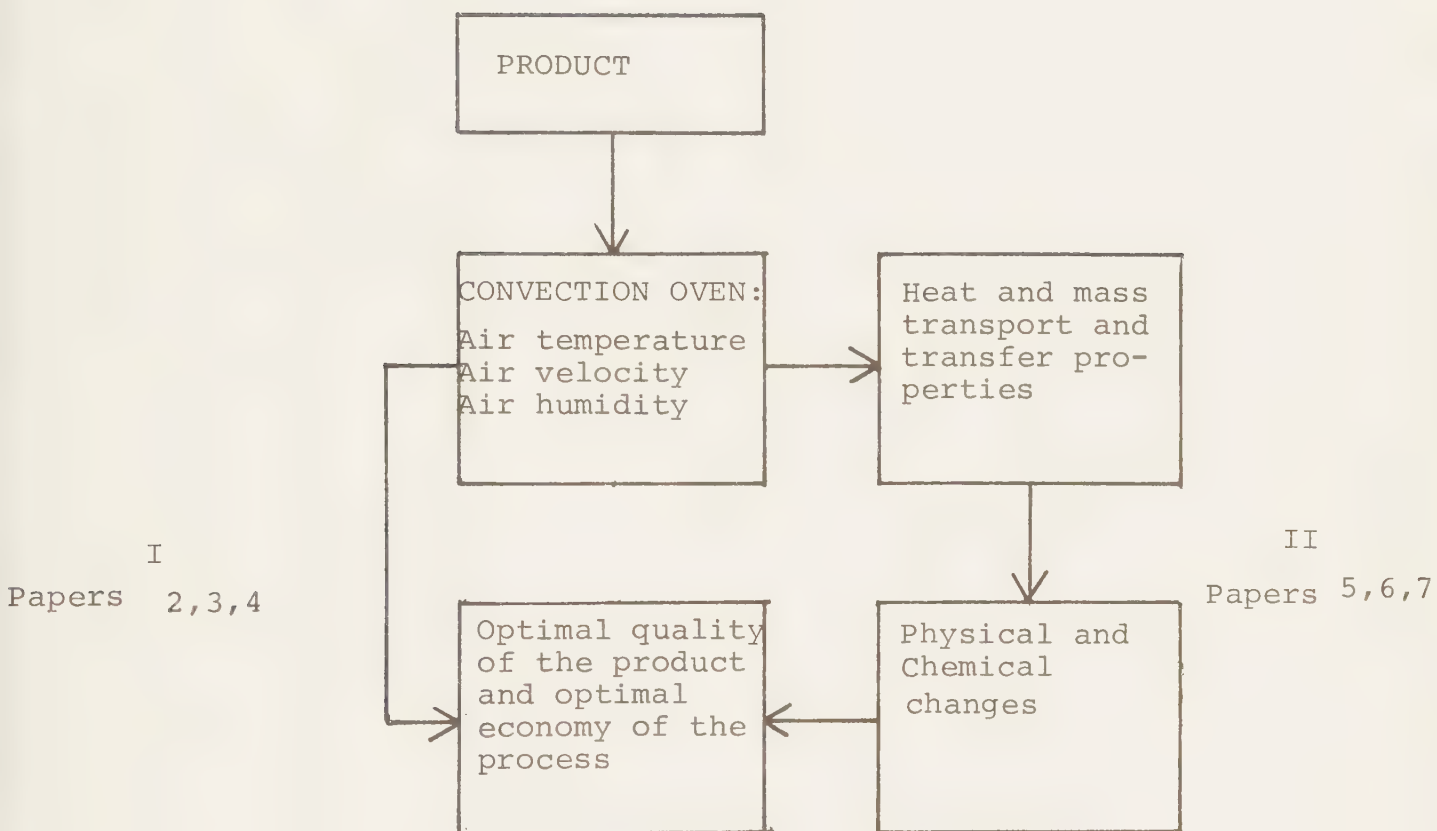
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Figure 1. The research programme.



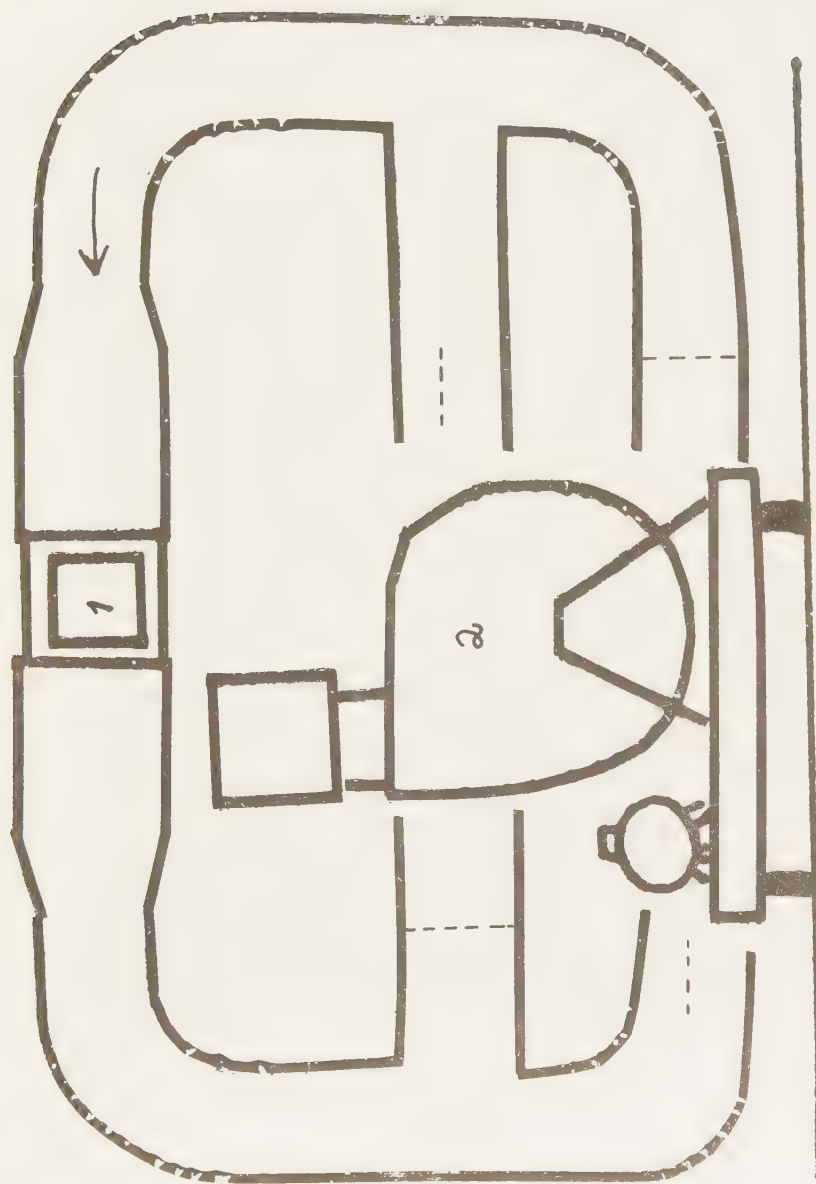
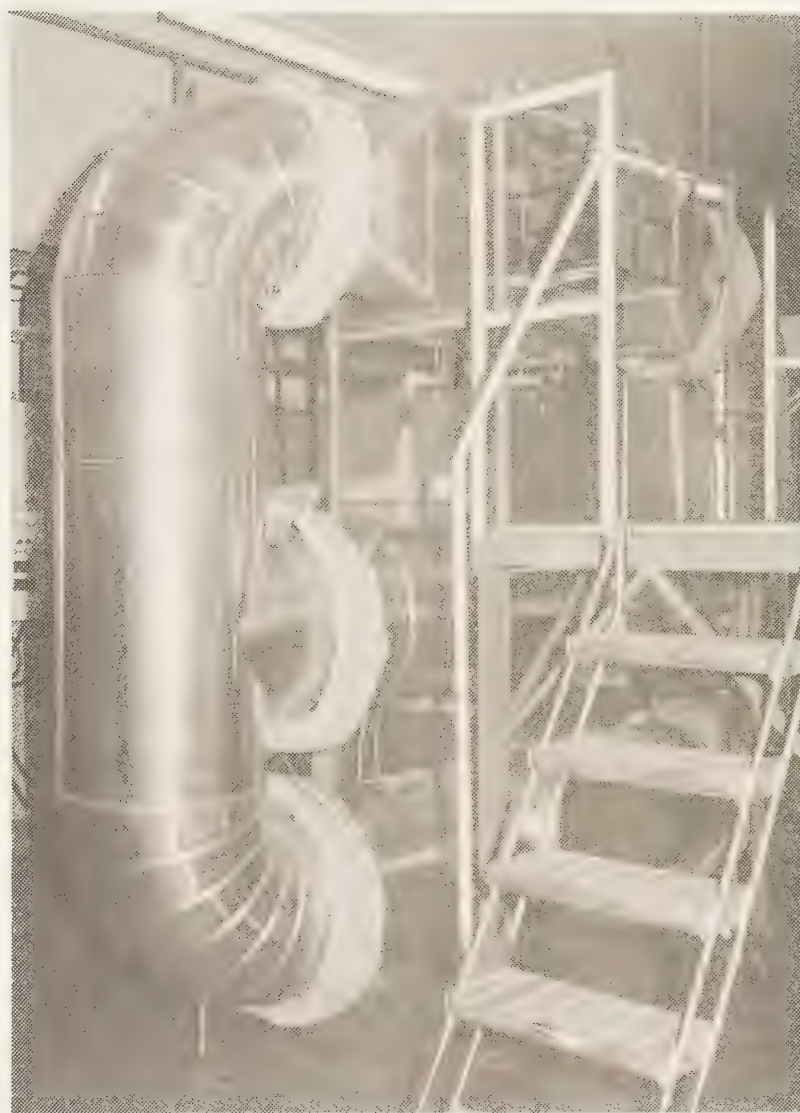


Figure 2. Principle of the research convection oven.

1. Oven cavity 2. Fan

Figure 3. Research convection oven.



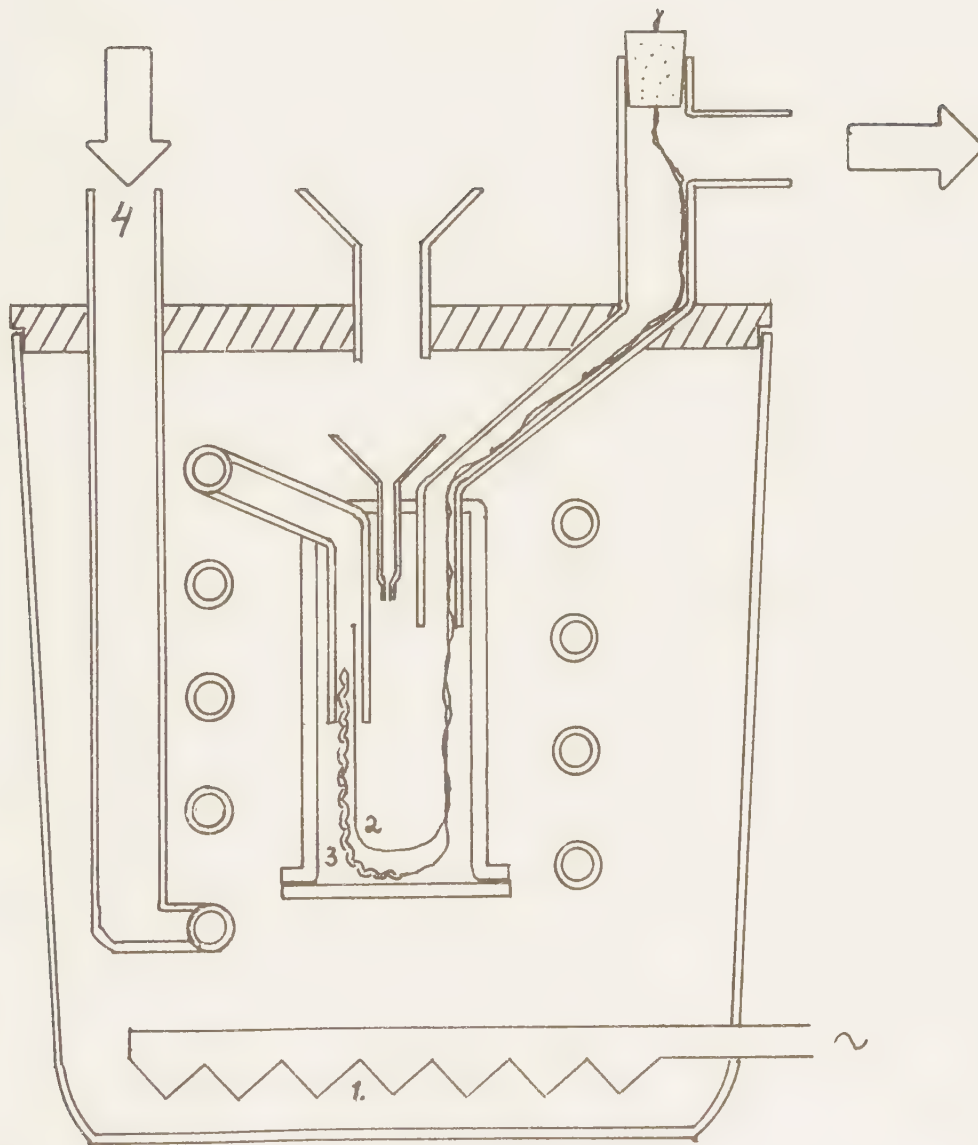


Figure 4. The hygrometer

1. Heater (400 W)
2. Thermocouple measuring dry temperature
3. Thermocouple measuring wet bulb temperature
4. Inlet of moist air from the oven

Figure 5. Heat transfer coefficient as a function of time.

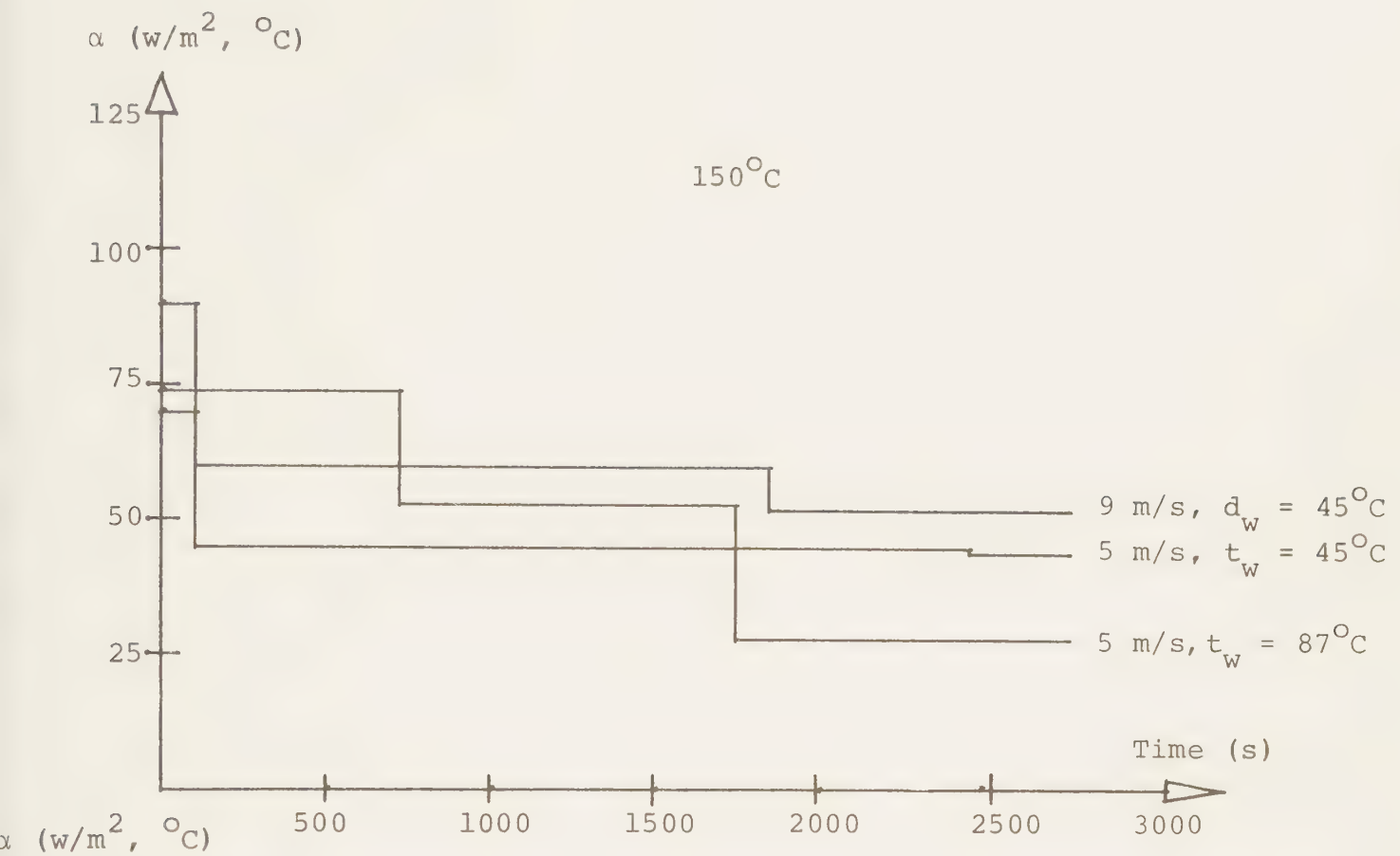


Figure 6. Temperature as a function of time at different distances from the surface 150°C, "dry" air.

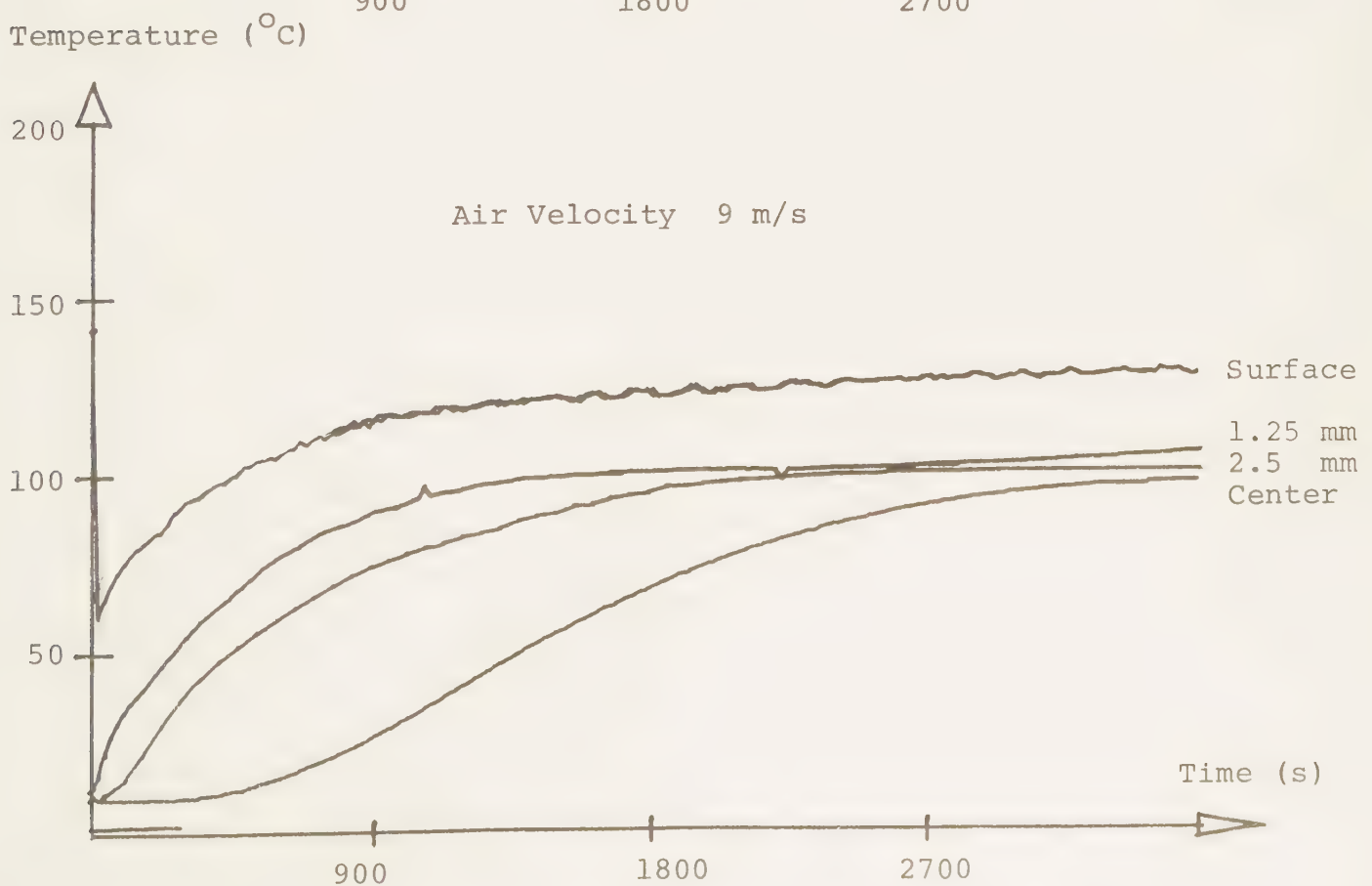
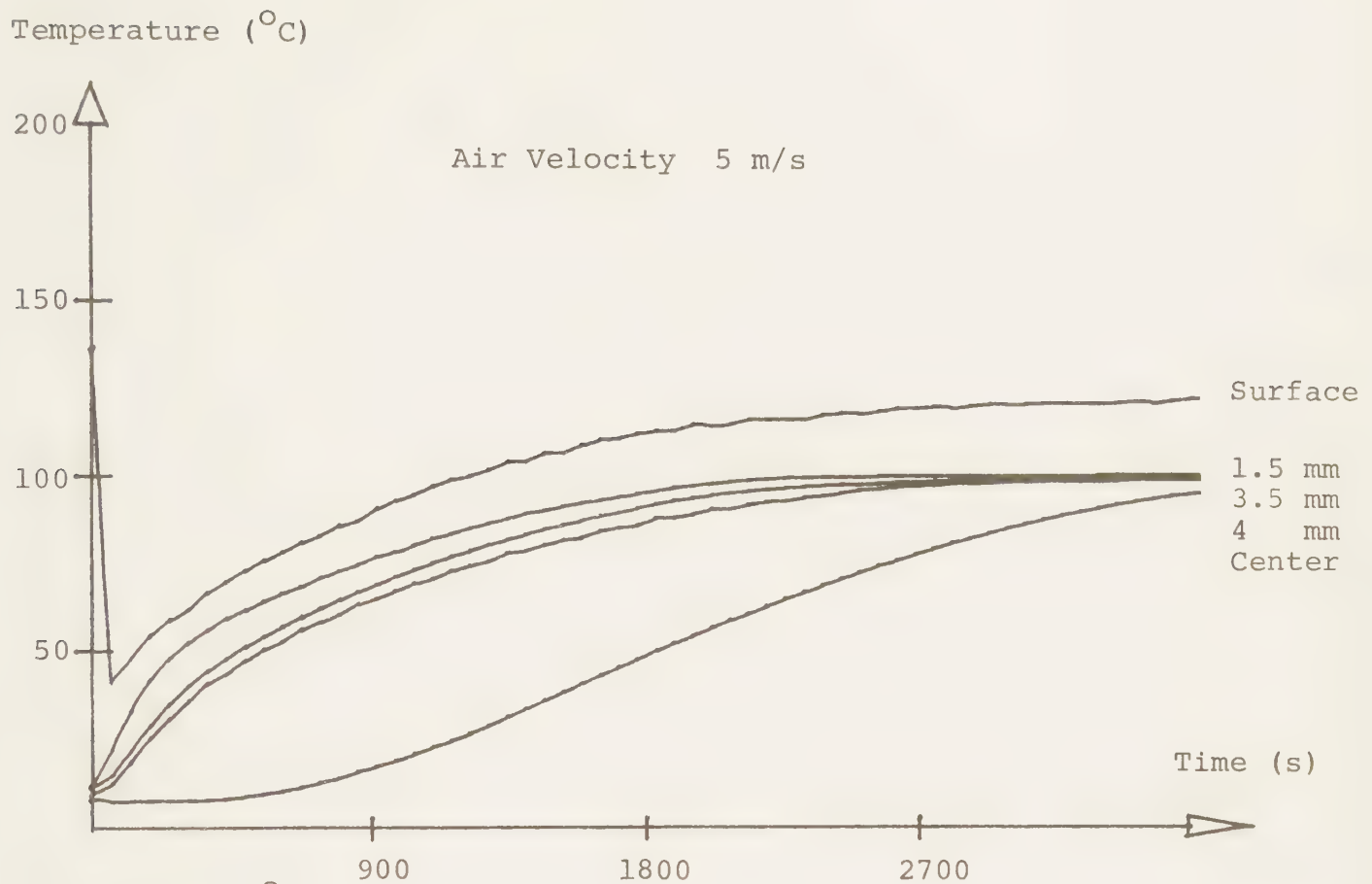


Figure 7. Temperature as a function of time at different distance from the surface. 225°C, "dry" air.

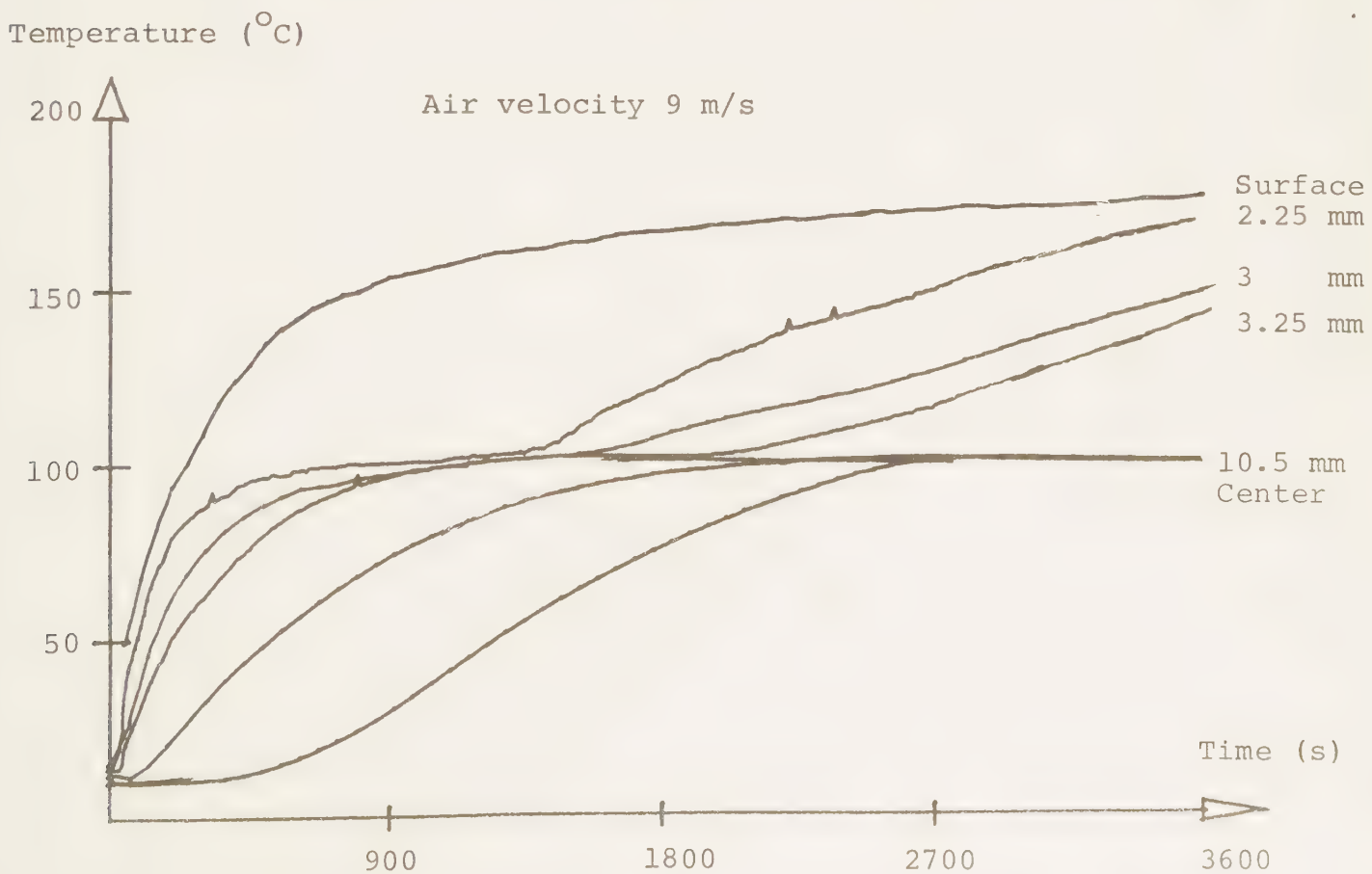
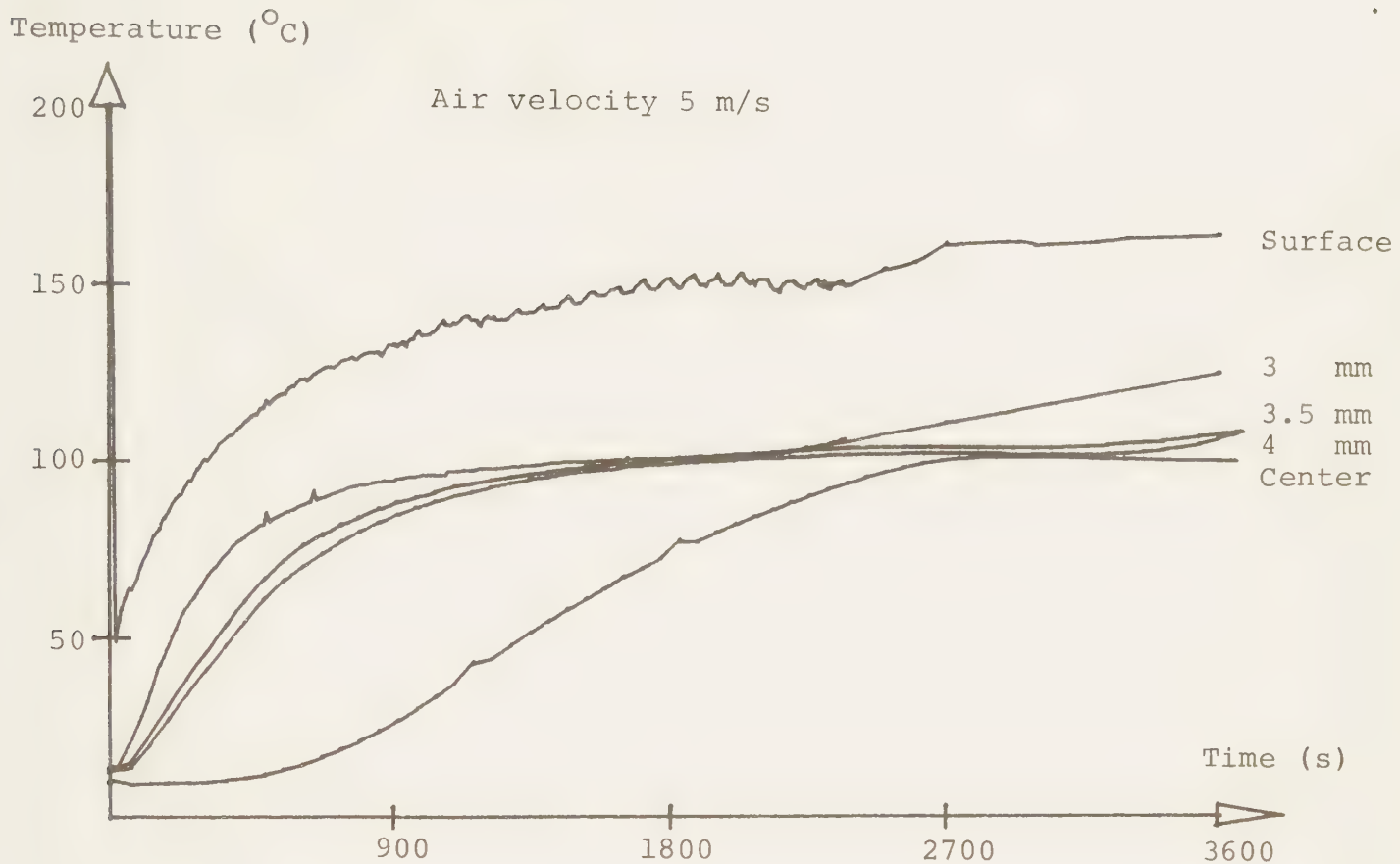
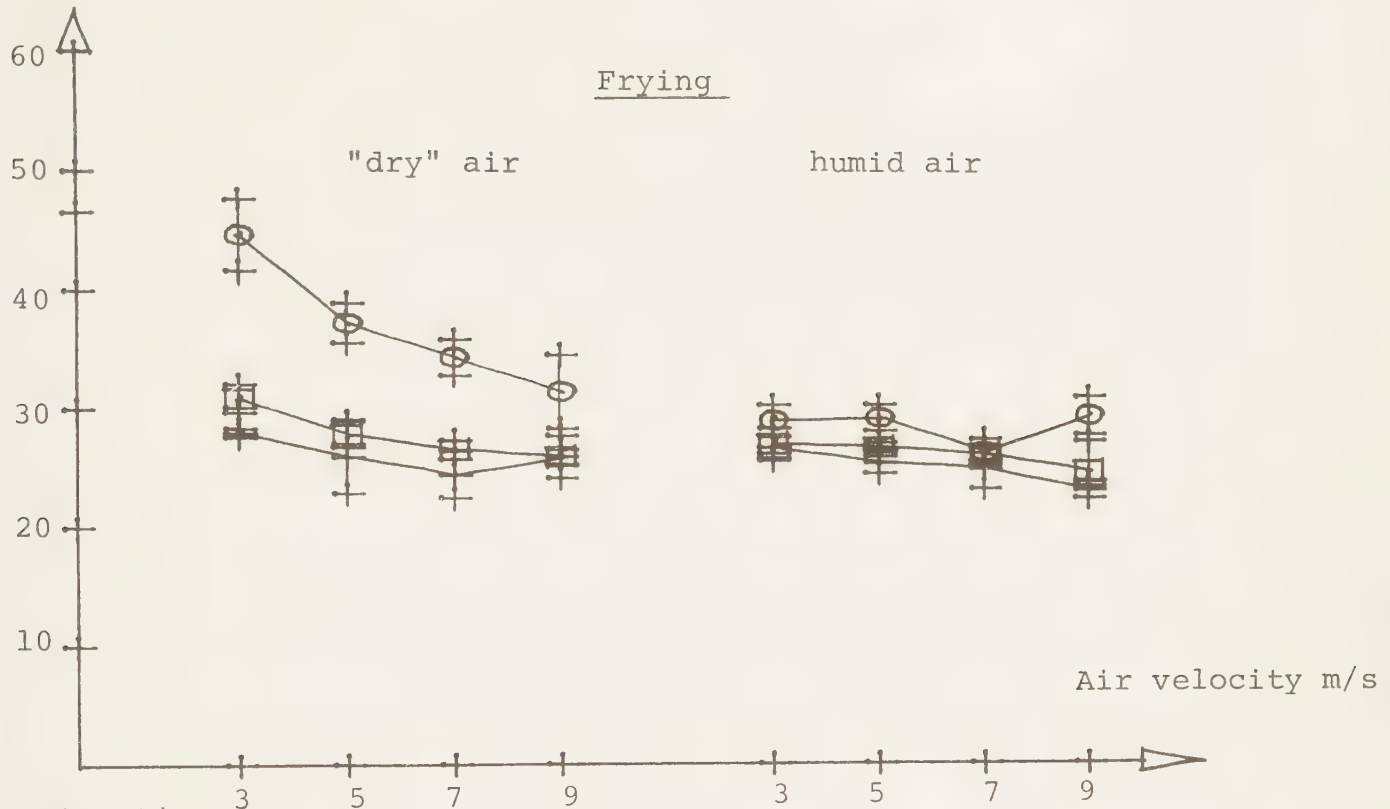




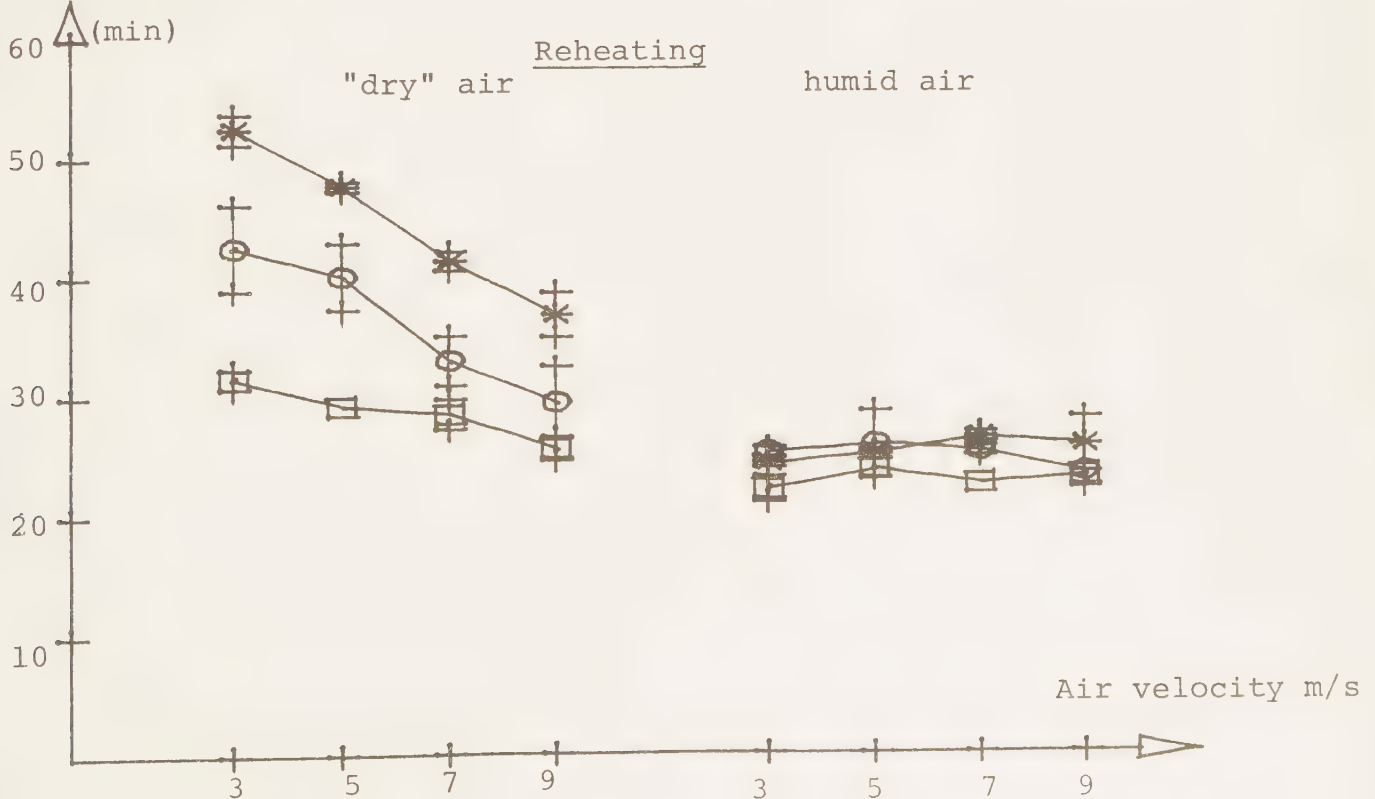
Figure 9. Heating time as a function of air Velocity. Temperatures are indicated by are parameters.

* 125°C o 150°C □ 200°C or 225°C
+ 300°C.

Frying time
(min)



Reheating time



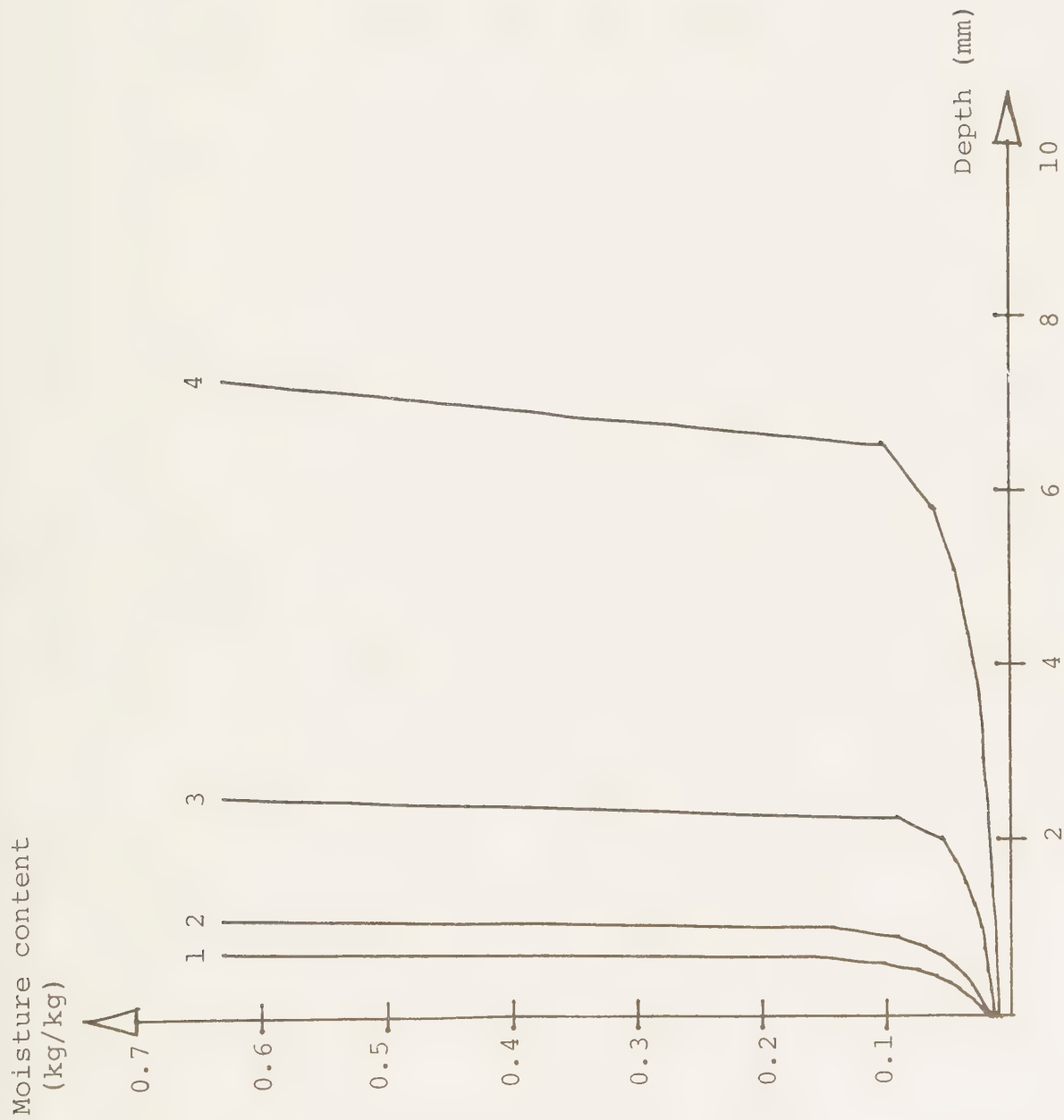


Figure 10. Moisture content of the crust as a function depth

1. 150°C, 5 m/s $t_w = 45^\circ\text{C}$ when center is 70°C
2. 150°C, 5 m/s $t_w = 45^\circ\text{C}$ after 2700 s. 3. 225°C, 9 m/s $t_w = 45^\circ\text{C}$ when center is 70°C. 4. 225°C, 9 m/s $t_w = 45^\circ\text{C}$ after 2700 s.

Figure 11. Water holding capacity of two different recipes as a function of temperature.

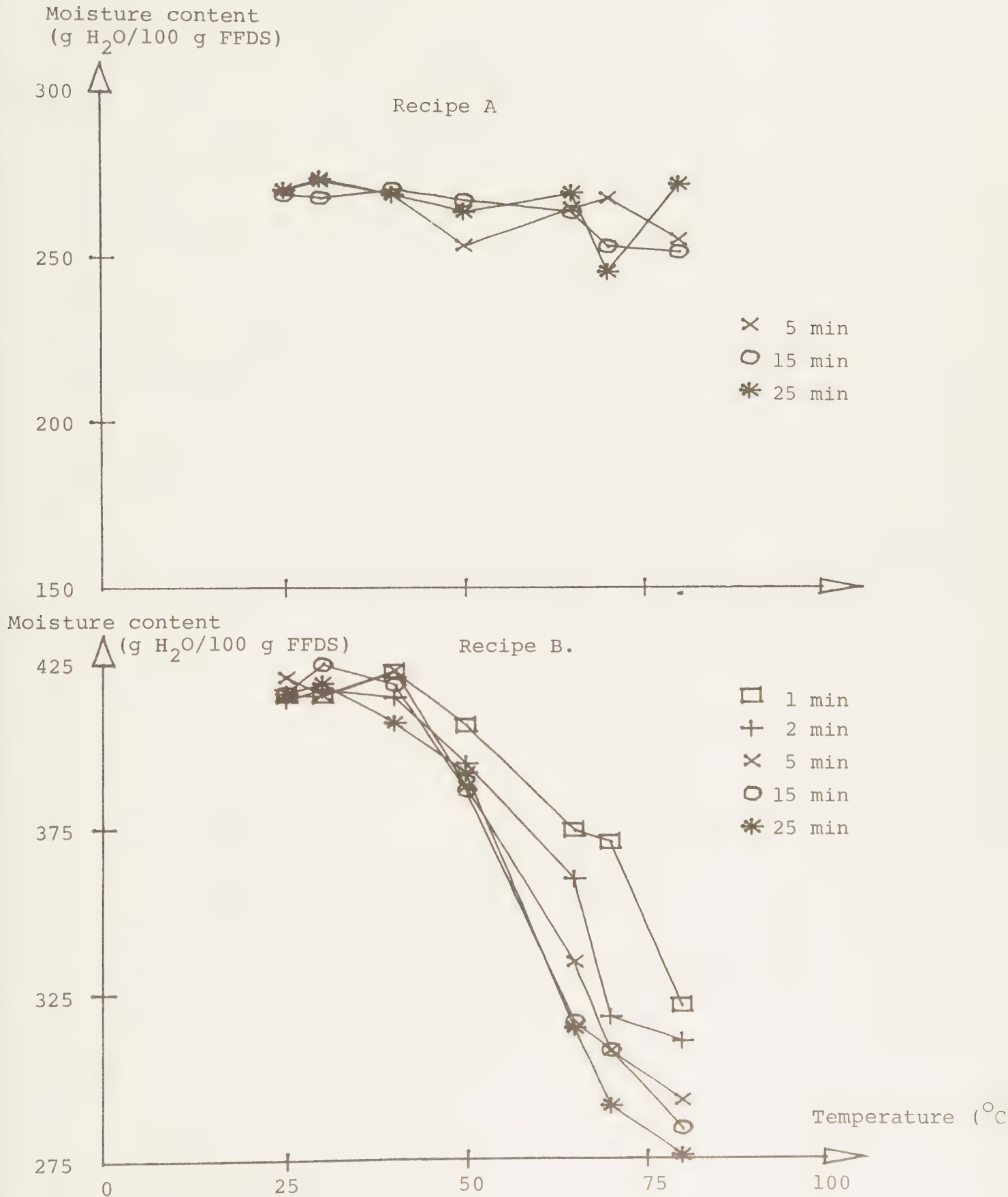


Figure 12. Weight losses as a function of air velocity.
 Temperatures indicated by
 * 125°C, o 150°C, □ 200°C and 225°C, + 300°C.

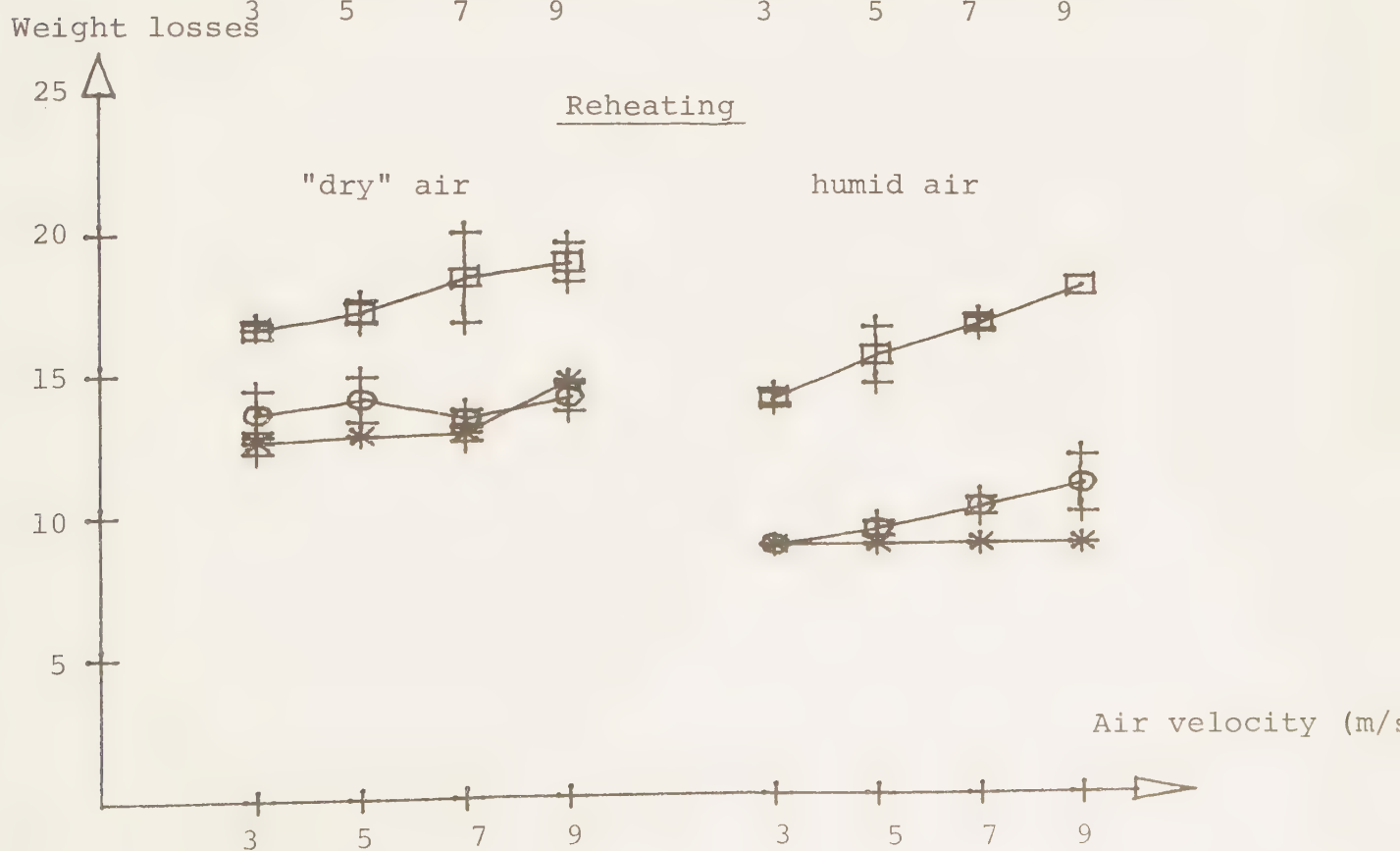
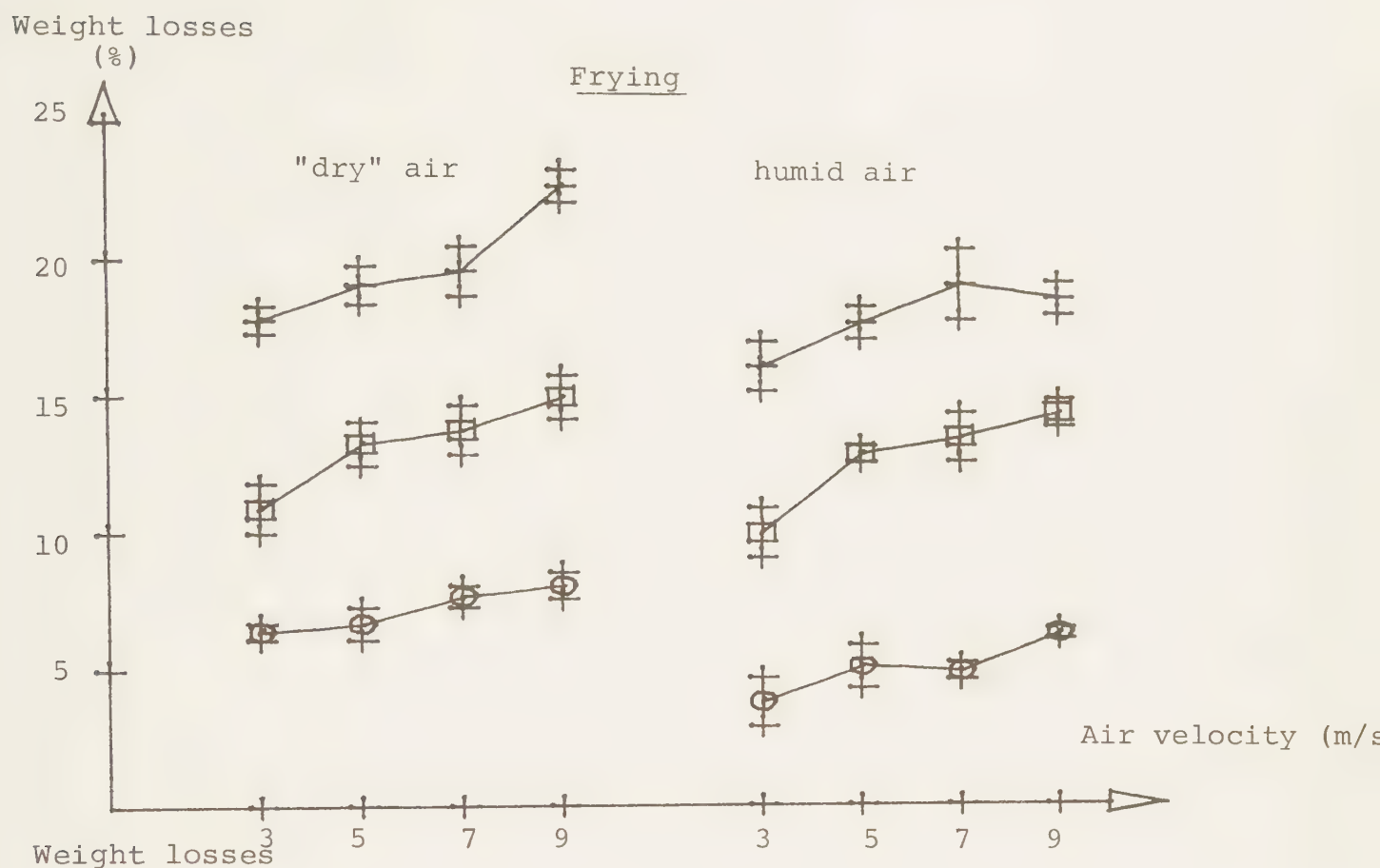


Figure 13. Crust colour as function of air velocity.

Temperatures are indicated by

* 125°C; o 150°C, 225 or 200°C and + 300°C.

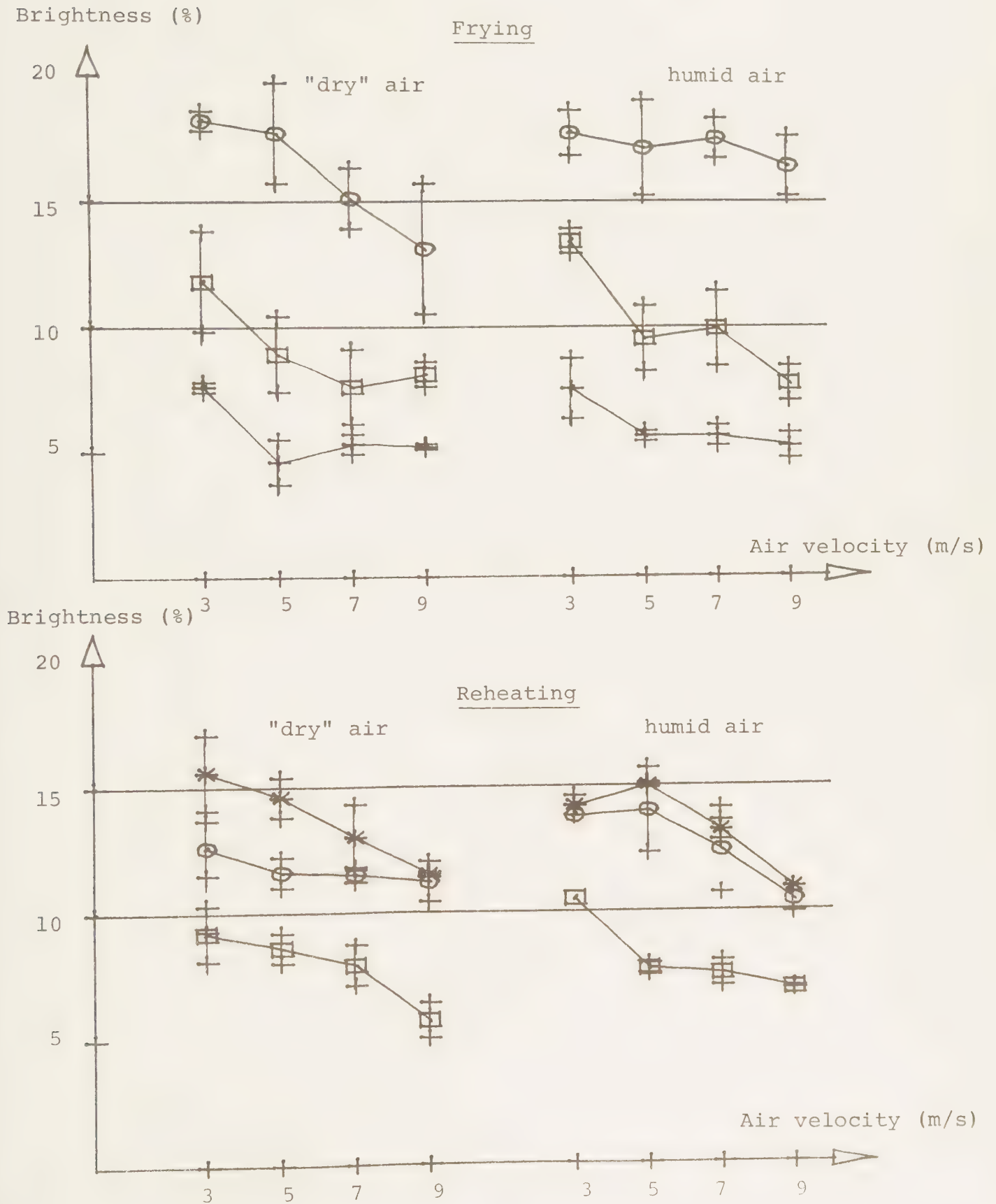


Figure 14. Temperature as a function of time at different distances from the surface.

1. From the model 2. Measured values.

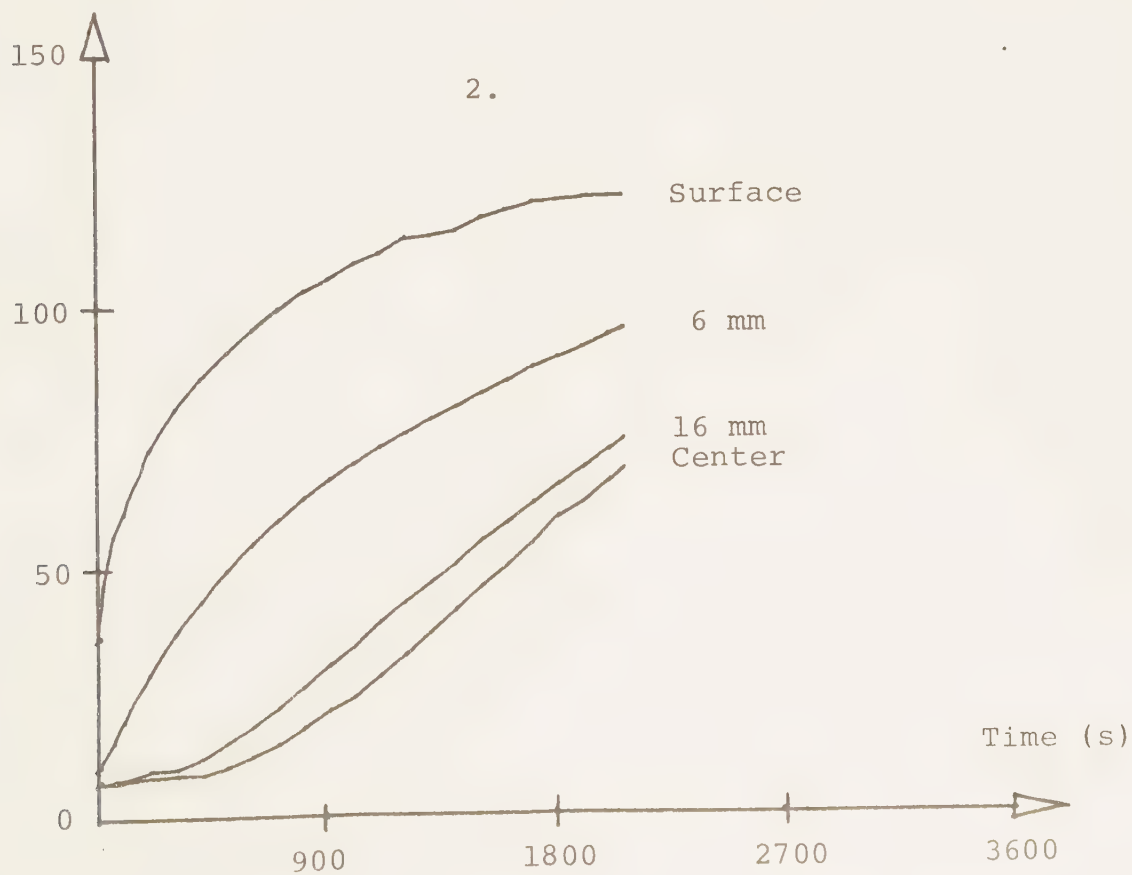
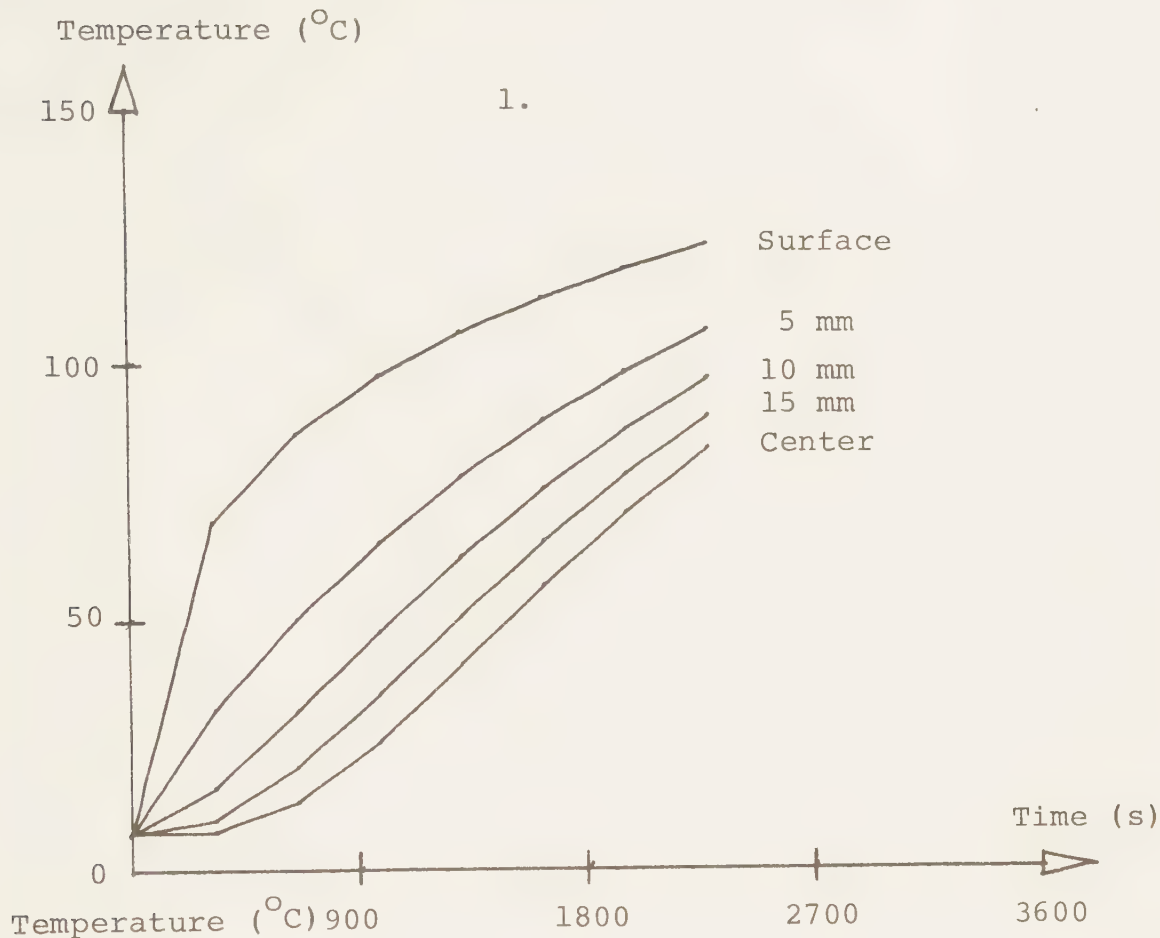
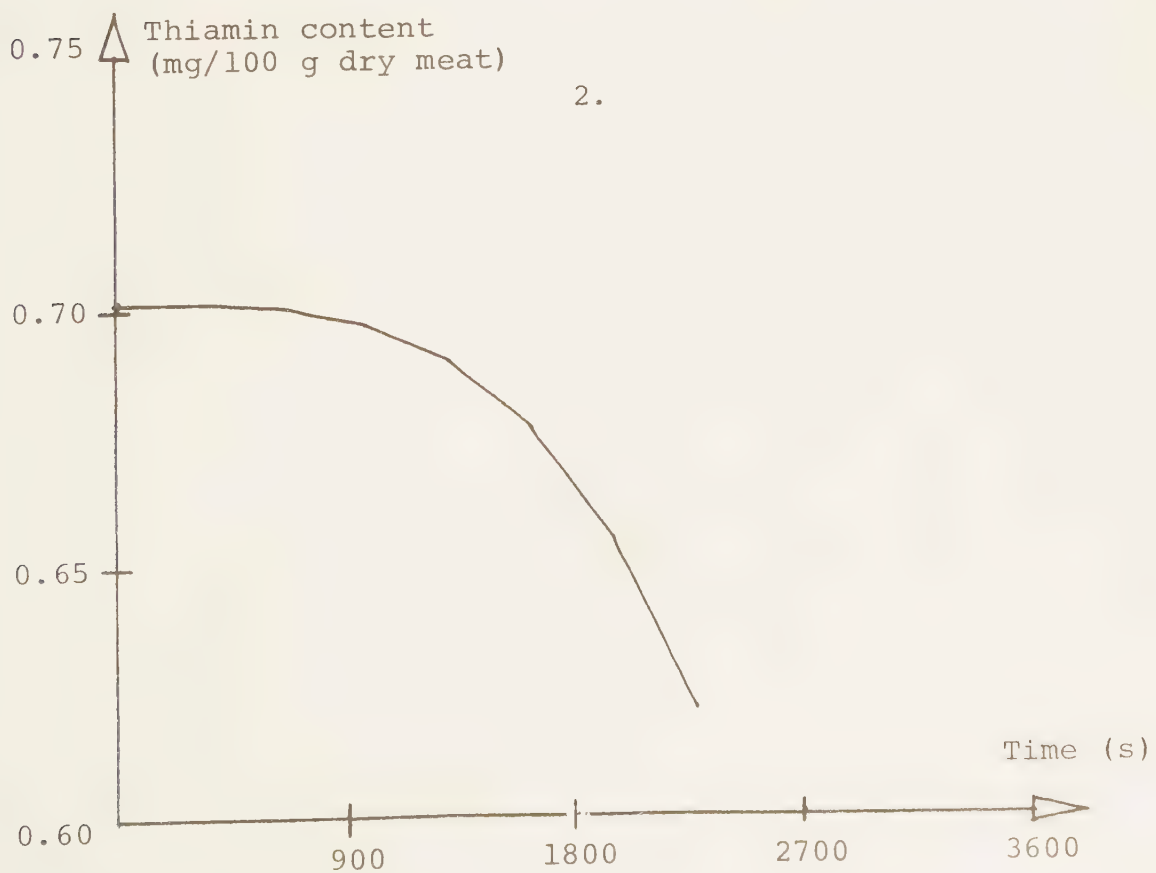
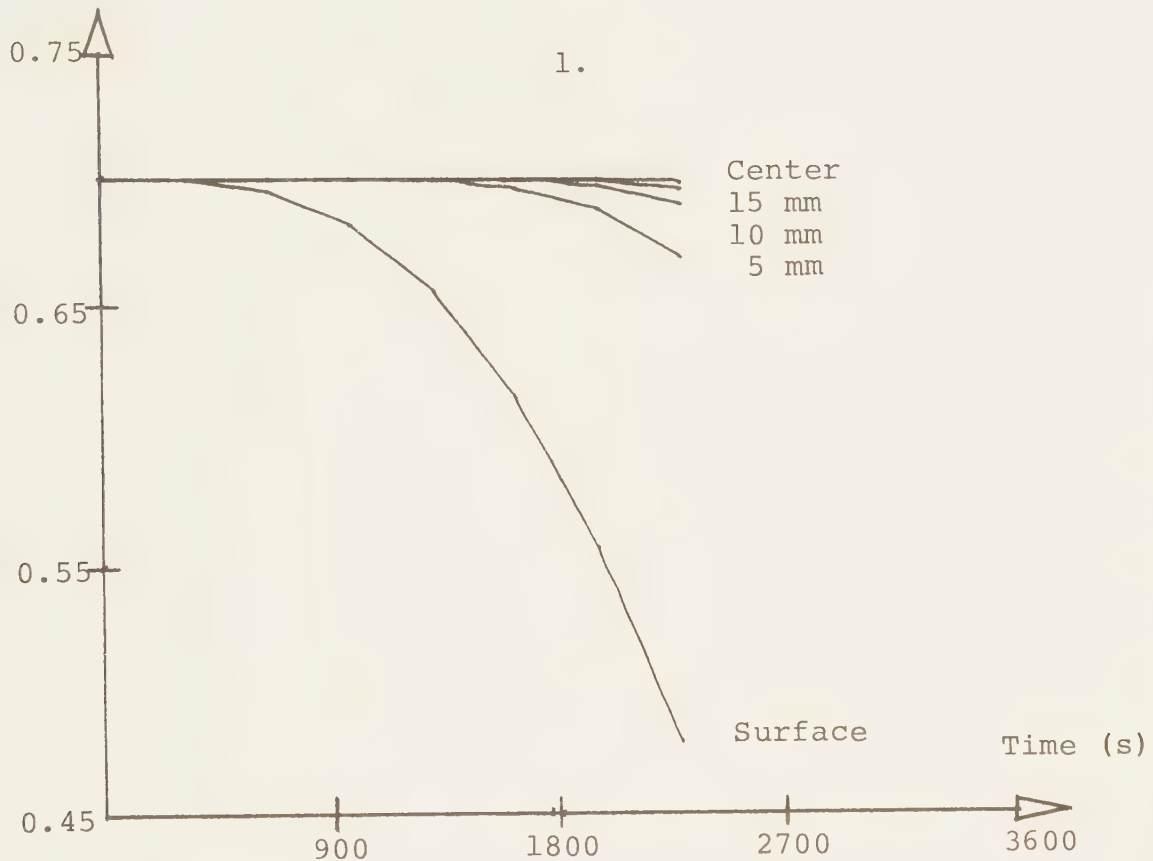


Figure 15. Thiamine content as a function of time.

1. At different distances from the surface

2. Mean value.

Thiamin content
(mg/100 g dry meat)



CONVECTION OVENS

By Christina Skjöldebrand, Division of Food Engineering,
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Despite the fact that more and more meals are either consumed outside the home or industrially prepared, the methods for preparation have not changed to any greater degree during the past decades. Attempts have been made to industrialize an age old handicraft where as modern processtechnology and the art of engineering have only to a small degree been applied to existing processes and methods. As a basis for the exploitation of modern techniques, the fundamental relationship between the heat transfer and heat transport to and within foods have to be studied and analysed.

Heat can be transported to the foodstuff in several different ways, such as by direct contact with the heated surface as on a frying table.

Another method of transporting heat is by radiation such as IR (Infrared) and a third method is through convection such as deep fat frying or convection heating with the help of air. Convection means that the heat transport occurs with the aid of a flowing gas or liquid. The product being heated is subjected to the higher temperature of the gas or the liquid.

What is a convection oven? A convection oven consists of an oven compartment in which a heated gas, often air, is circulated with the aid of a fan. Another name is a hot air oven. The original use was for baking. Fig. 1 shows the principle. To speed up the heat transport and eliminate waste, a steam generator is connected to the oven whereby a mixture of steam and air is used. The use of moist air decreases the water expulsion in the heated substance.

This type of heating equipment is much used in catering establishments and in industry. The size of existing ovens varies from large continual ovens for industrial use to small cupboards for the heating of single packages in catering. An example of a Swedish oven designed for continual use in industry is the Electrolux Stekmaskin which consists of a number of sections with a fan in each section.

Most convection ovens, however, consists of one compartment with a fan according to fig. 1.

Examples of Swedish manufactures/supplies appart from Electrolux are

Capro Produkt AB
 Elektro Dahlén AB
 C G Forselius AB
 Henning R AB
 Iwema Food Machinering AB
 Kopal Industrier AB
 Maskin
 Metos Storkök AB
 AB Svenska Bakugnsfabriken
 Svenska Stephan AB
 Tipe Revent AB

How is a convection oven used?

ISR the Institute for the Rationalization of Catering have in a number of rapports presented the market situation and have undertaken studies of the uses of convection ovens. (1, 2, 3). Here at the division of Food Engineering in Alnarp we have interviewed a number of caterers and food industries about the use of convection ovens, to obtain information as a preparation for our research program (4). Nine different ovens were examined from five different manufactures. The object was a representation of both small and large ovens from different areas of application.

This report gave the result that hot air ovens were mostly used for frying. They were here used either in place of or as a complement to frying cupboards and frying tables. In many catering establishments these ovens were used primarily for thawing frozen products. The types of products that are fried in convection ovens varies but are generally well tested products such as sausage, chicken parts etc. The ovens were generally considered to be flexible with many varying uses. The interviews showed that the temperatures used were usually between 150°C and 250°C depending on the product to be heated. The ovens with a mixture of steam in the air do not give any possibility of control of the amount of steam in the mixture. Very few ovens allow variations in the velocity of the air.

What needs is there for research about convection heating?

A study of the literature in the field shows that very little study has been made of heat transfer and heat transport by convection heating within the food field. Some research is being carried out in Eastern Europe, such as Czechoslovakia and even in Karlsruhe, Western Germany.

About 4 million meals are served every day outside the home in Sweden. This situation necessitates all the more an effective and practical heating technique. Of greatest importance is the need to examine how to best use the technique available today. From a technical point of view the effect of the air humidity on the frying process and the weight loss is of special interest. It must be possible to establish the optimal steam/air relationship for the heating process of every single product with regard to oven temperature and air velocity. On a more general basis it is of great interest to study the effect of the heating on the quality of the product, especially nutritional value.

Research projects on convection ovens.

The composition of the experimental oven. During the past year we have at the division of Food Engineering started a research project with the aim of fundamentally studying the heating

process in a convection oven. An experimental oven has been built in the work shop at the Chemical Centre in Lund. The aim has been a piece of apparatus which will enable us to have complete control of the oven convection i.e we need to have control over the temperature, humidity and velocity of the air. We need to know exactly how product is heated to be able to establish the effect at the various parameters. The oven is built like a wind tunnel with the possibility of momentarily altering the course of the air in the oven cavity. Fig. 2 shows the principle of construction and Fig. 3 is a photograph of the oven. The dimensions of the oven cavity are 325 x 325 x 325 mm. There is space for three shelves of stainless steel netting. There is also equipment for measuring air humidity, air velocity and a thermocouple for measuring and regulating the oven temperature. The air stream is dispersed with the aid of guide plates and finely meshed netting to obtain the same velocity in the whole cross section of the product. The velocity can be varied without limitation from 2-12 m/s and the air temperature from 20-400°C. Steam is applied in front of the fan which in turn is placed in front of the heating element which has an effect of 15 kW. Air humidity can be varied from 0-1 kg steam/kg humid air.

The temperature inside the product is measured with a thin thermocouple according to a technique previously used at the division of Food Engineering (5). The oven door and the shelves for the products are attached to wheels with a back wall which enables the oven compartment to be pulled out without disturbing the system. This means that the thermocouple which runs through a hole in the door can be inserted in to the product which can be placed on the steel netting and the whole oven can then be pushed back into the warm air without disturbing the balance.

The thermocouple is connected to a so called datalogger where all data is collected in the form of voltage and is then transferred to a punched tape. This is then translated to suitable information with the help of a table computer. The computer is connected to a plotter where every individual

time/temperature relationship or any other relationship in the product can be studied.

Even the air humidity and velocity which is first translated from pressure to voltage which is registered on the data-ized logger. This collecting unit can register ten points per second which means that the temperature in the product can be followed just about continuously. The upper roof of the oven compartment has a large plane of glass which enables study of the appearance of the product.

How the research is planned.

The research project is to be divided into two main sections which are related to each other. Firstly the effect of the various parameters will be studied such as air velocity, air humidity, air temperature and heating time for the various products, loss of water and the appearance of the crust. The various product geometries, will also be studied. In this connection the study of different recipes and the effect of the frying fat on the crust and how the crust is formed will be carried out. The effect of frying on the nutritional value will be studied too.

The second part will consist of more theoretical calculations. Heat transfer from air to surface and its connection with the formation of crust will be examined. Other objects of study are the importance of air humidity and heat transport inside the products. A pilot study in the shape of a thesis was carried out in the autumn of 1975. In this project the thermal diffusivity of the meat products was examined at various meat temperatures with three different air temperatures, three different velocities and three different humidities. The surface temperature was also studied and its connection to surface colour. It is, however, difficult to measure the surface temperature with the help of thermocouples

Plan for the near future.

Our plans for the near future are connected to phase one in the research plan. A series of trials will be carried out together with the division of Applied Nutrition in Lund,

whereby the effect of the frying of minced meat products in convection ovens will be studied. The frying will be carried out with three different oven temperatures and for each temperature air humidity and air velocity will be suitably varied. The product is to be heated to a temperature of 70°C in the centre and the temperature in various parts of the product will be followed continually. The fried product will be analyzed with regard to nutritional value, surface colour and water content. We hereby hope to obtain interesting information about the effect of the characteristic process variables of the convection oven on the heating process as well as the effect of heat on the biological availability of the essential amino acids.

During the past 4-5 years research has been carried out at the division of Food Engineering in the field of deep fat frying. The convection oven described above increases our equipment in this field and enables us to study the frying process in detail. Our aim is to establish optimal values for processing with regard to quality and nutritional value which will benefit catering industry and ultimately the consumer.

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Särtryck ur **Livsmedelsteknik**
nr 8 (november) 1976

Konvektionsugnar

Av Christina Skjöldebrand

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Även om produktionen av industriellt tillagad mat och uteätandet ökar i vårt land, har tillagningsmetoderna inte nämnvärt förändrats under flera årtionden. Man försöker industrialisera ett hantverk, som har funnits i många år. Modern processteknik och ingenjörskonst har hittills endast i ringa omfattning applicerats på befintliga processer och metoder. För att få underlag för ett utnyttjande av modern teknik, måste bl a de fundamentala sambanden för värmeöverföring till och värmetransport i livsmedel kartläggas och belysas. Vid tillagning av mat kan värme överföras till livsmedlet på flera olika sätt, t ex genom kontakt, d v s livsmedlet ligger i direkt kontakt med upphettade ytor från vilka de upptar värmen som på ett stekbord. Ett annat sätt att överföra värme är genom strålning exempelvis med IR (infraröd)-strålning och ett tredje sätt är genom konvektion, t ex med fritering i fett eller konvektionsvärmning med hjälp av luft. Med konvektion menas att värmeöver-

föringen sker med hjälp av en strömmande gas eller vätska. Den produkt som skall värmas utsätts för den strömmande gasens eller vätskans högre temperatur.

Vad är en konvektionsugn?

En konvektionsugn består av ett ugnsutrymme, i vilket en uppvärmd gas, oftast luft, bringas att cirkulera med hjälp av en fläkt. Ett annat namn är varmluftsgn. Den ursprungliga användningen var som bakugn.

Figur 1 visar en principbild. För att påskynda värmeöverföringen och minska svinn, finns ibland en ånggenerator kopplad till ugnen för att i stället för torr luft använda en blandning av luft-ånga. Om fuktig luft användes, är nämligen vattenavgången från produkten mindre än om torr luft användes.

Denna typ av uppvärmningsutrustning användes mycket både i storhushållen och industrin. Storleken varierar på de befintliga ugnarna ifrån stora kontinuerliga ugnar för industrin till små skåp för enstaka förpackningar i storhushållen. Ett exempel på en svensk-tillverkad kontinuerlig industriugn är Elektrolux stekmaskin som består av ett antal sektioner med en fläkt i varje sektion.

De flesta konvektionsugnarna består dock av ett skåp med fläkt enligt figur 1. Exempel på svenska tillverkare/leverantörer förutom Elektrolux är Capro Produkt AB, Elektro Dahlén AB, G C Forselius AB, Henning R AB, Iwema Food Machinery AB, Kopal Industrier AB, Maskinkonstruktioner, Metos Storkök AB, AB Svenska Bakugnsfabriken, Svenska Stephan AB, Tipe Revent AB (3).

Hur användes konvektionsugnarna?

Institutet för Storhushållens Rationalisering (ISR) har i ett antal rapporter redovisat dels marknadsöversikter, dels undersökningar över konvektionsugnens användningsområden (1, 2, 3). Dessutom har vi vid Livsmedelsteknik i Alnarp genomfört en intervjuundersökning vid olika storhushåll och i livsme-

delsindustrier om användningen av konvektionsugnar för att få information inför vårt forskningsprogram (4). Nio olika ugnar valdes ut. De representerade fem olika fabrikat. Avsikten var att såväl ett urval av små som stora ugnar från olika användningsområden skulle vara representerade. Ur denna rapport framkom bl a att varmluftsgnarna mestadels användes som stekapparater. De fungerar då som ersättning för eller komplement till stekskåp och stekbord. I många storhushåll användes de dock till tining av djupfrysta produkter. De produkttyper som steks i konvektionsugnar varierar och är nog utprovade produkter såsom korv, kycklingdelar m m. Ugnarna anses i allmänhet vara flexibla med många möjligheter till olika användningsområden. Av intervjuerna framgår också att man vanligen använder sig av ugnstemperaturer mellan 150°C och 250°C, helt beroende på vilken produkt som man avser att värma. De ugnar som har ånginblandning i luften ger ingen kontrollmöjlighet över hur stor del ånga som inblandas. Mycket få har möjlighet till variation av luftens hastighet.

Behövs forskning om konvektionsupphettning?

Av litteraturundersökningar framgår att mycket litet forskning bedrivits för att undersöka värmetransport och värmeöverföring vid konvektionsvärmning inom livsmedelsområdet. En del forskning pågår dock i Östeuropa, bl a i Tjeckoslovakien och även något i Karlsruhe i Västtyskland.

Cirka fyra miljoner måltider per dag serveras i dag i Sverige utanför hemmet. Detta kräver och kommer att än mer kräva en bra och effektiv, praktisk applicerbar uppvärmningsteknik och framför allt bör en kartläggning genomföras över hur befintlig teknik bäst skall användas. Ur teknikerns synpunkt är ånginblandningens, d v s luftens fuktighets inverkan på stekningsförloppet och svinn, speciellt intressant. Man bör kunna finna optimala ånga/luftförhållanden för värmningsförloppet för varje enskild produkt och i förhållande till ugnstemperatur och lufthastighet. Men allmänt är det av stort intresse att veta uppvärmningens inverkan på kvalitet och framför allt näringsvärde.

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Forskningsprojekt om konvektionsugnar

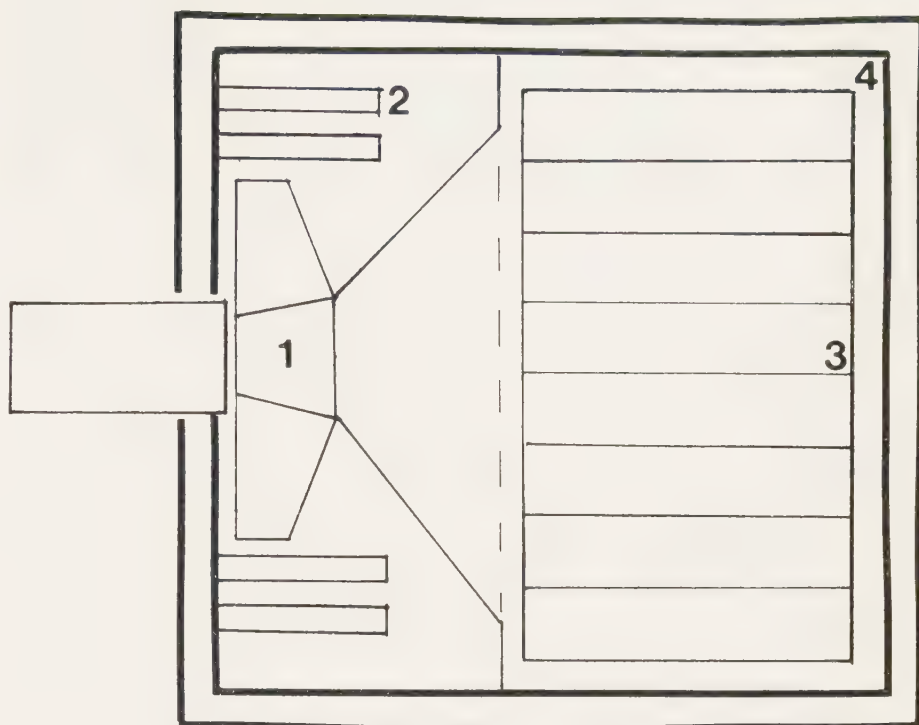
Försöksugnens uppbyggnad

Under det senaste året har vi på Livsmedelsteknik startat ett forskningsprojekt som ingående skall försöka studera uppvärmningsförloppet i en konvektionsugn. En försöksugn har projekterats och byggts i Kemicentrums verkstad i Lund. Målet har varit en apparat som i våra försök skall ge helt kontrollerbara ugnsförhållanden, d v s vi vill ha exakt kontroll över luftens temperatur, fuktighet och hastighet. Vi vill veta exakt under vilka förhållanden som livsmedlet uppvärms för att sedan kunna utreda de olika parametrarnas inverkan på produkten.

Ugnen är byggd som en vindtunnel med möjligheter att momentant ändra luftriktningen i ugnsutrymmet. Figur 2 visar en principskiss över ugnens uppbyggnad och figur 3 visar ett fotografi av ugnen. Ugnsutrymmets dimensioner är $325 \times 325 \times 325$ mm. Där finns plats för tre hyllor av rostfritt stål. Dessutom finns mätutrustning för luftfuktighet, lufthastighet och ett termoelement för mätning och reglering av ugnstemperatur. Luftströmmen fördelas med hjälp av ledplåtar och finmaskiga nät så att samma hastighet erhålles i hela tvärsnittet när den träffar produkten. Hastigheten kan steglöst varieras från 2–12 m/s och luftens temperatur från 20–400°C. Ånga tillsetts före fläkten som i sin tur är placerad före värmeelementen med en effekt av 15 kW. Luftfuktigheten kan varieras från 0–1 kg vattenånga/kg fuktig luft.

Temperaturen i produkten mätes med hjälp av tunna termoelement i enlighet med en tidigare genomförd undersökning vid Livsmedelsteknik (5). Ugnslucka och hyllor för produkterna är upphängda i en vagn med en bakvägg som är så stor att om luckan drages ut så är ändå systemet slutet. Detta betyder att termoelement, vilka löper genom hål i luckan, kan monteras i produkten utanför den varma luften och dessutom kan produkten läggas på plats på stål nätet. Därefter skjuts luckan plus hyllor med hjälp av hjul in i den varma luften utan att balansen störes.

Termoelementen är kopplade till en sk datalogger. Här samlas alla data i form

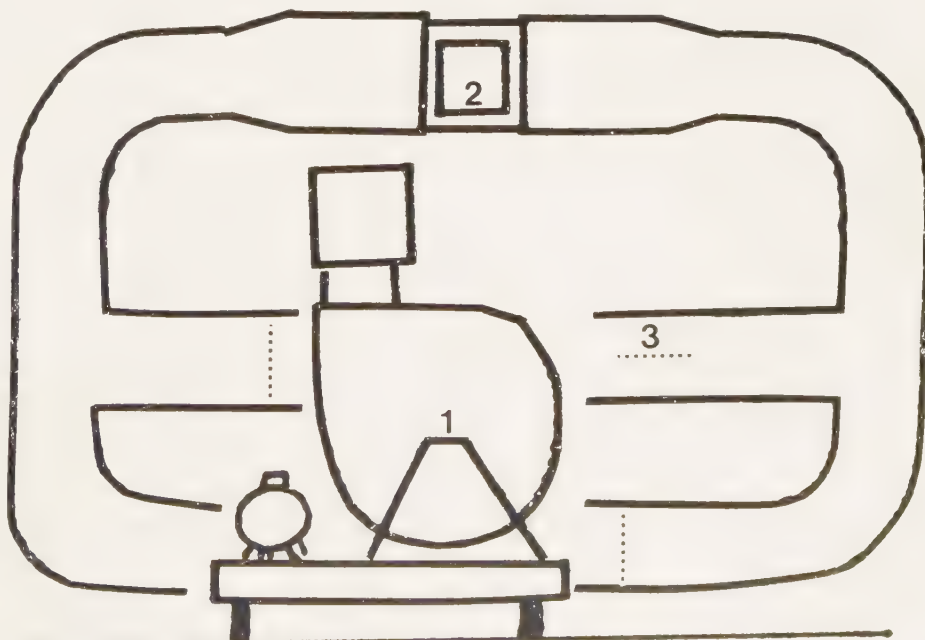


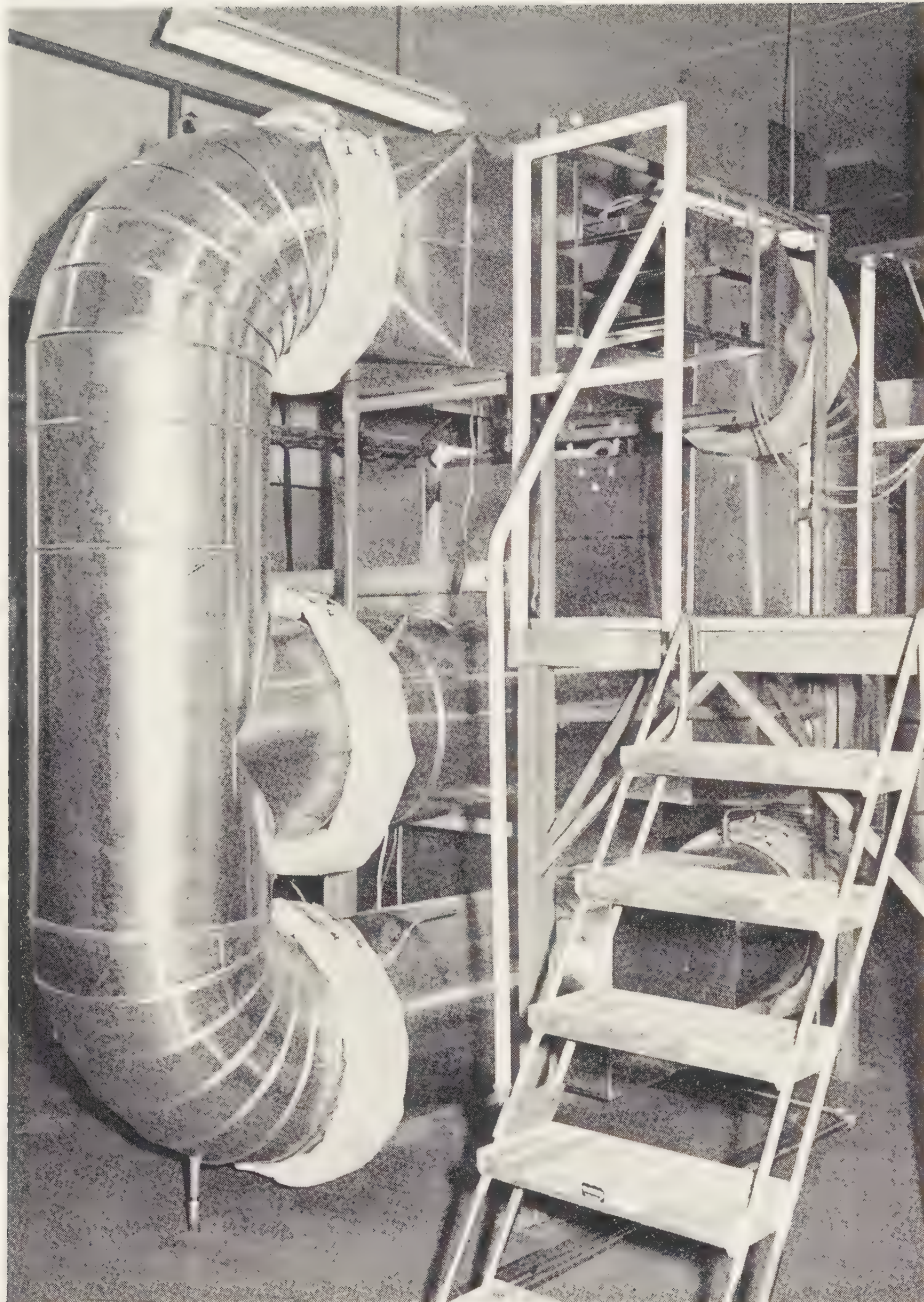
Figur 1. Principbild på en konvektionsugn.

1. Fläkt
2. Värmeelement
3. Hyllor för produkt som skall värmas
4. Ugnsutrymme

Figur 2. Principbild på konvektionsugnen i Alnarp.

1. Fläkt
2. Ugnsutrymme
3. Spjäll för reversering av luft





Figur 3.
Konvektionsugnen i Alnarp.

des ytemperaturen och dess samband med ytfärgen. En svårighet är att mäta ytemperaturen med termoelement.

De närmaste planerna

Våra närmaste planer hänför sig till ovannämnda etapp ett i forskningsplanen. Vi skall genomföra en försöksserie tillsammans med Industriell näringslära i Lund, varvid stekningens inverkan på köttfärsprodukter i konvektionsugnar skall undersökas. Stekningen skall ske vid tre olika ugnstemperaturer och för varje temperatur skall luftfuktighet och lufthastighet varieras på lämpligt sätt. Produkten skall värmas till 70°C centrumtemperatur och temperaturen på olika ställen i produkten skall kontinuerligt följas. Den stekta produkten kommer att analyseras med avseende på näringsvärde, ytfärg och vattenhalt. Vi hoppas med detta få fram intressanta upplysningar om inverkan av de för konvektionsugnen karaktäristiska processvariablerna på värmningsförlopp samt värmningsens effekt på de essentiella aminosyrornas biologiska tillgänglighet.

Vid Livsmedelsteknik pågår sedan 4—5 år tillbaka forskning inom stekningsområdet väsentligen avseende fritering. Med den beskrivna konvektionsugnen utökas sålunda vår utrustning på området och vi får härmed ökade möjligheter att detaljstudera bla stekningsförloppen. Vårt syfte är att med hänsyn till kvalitet och näringsvärde söka få fram optimeringsunderlag för processerna till nytta för storhushåll, industri och ytterst konsument.

Referenser

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- (5) Hallström, B., Sörenfors, P. Zur Wärmeübertragung bei thermischen Zubereitungsverfahren der Fleischerzeugnisse. Fleisch 29 (1975), 185—188.

av spänning och överföres sedan till en hålremsa. Denna översättes till lämplig information med hjälp av en bordsdator. Till bordsdatorn hör en skrivare där varje enskilt tid/temperaturförlopp i produkten eller annat förlopp kan upprättas. Även luftfuktighet och -hastighet, som först översättes från tryck till spänning tas upp på dataloggern. Tio punkter per sekund kan detta uppsamlingssystem registrera, vilket betyder att temperaturförloppet i produkten kan följas så gott som kontinuerligt. På ovansidan av ugnsutrymmet finns placerat en stor glasruta där produktens utseende kan studeras.

Forskningsarbetets uppläggning

Forskningsarbetet kommer att delas i två huvuddelar, som är kopplade till varandra. Först skall vi studera inverkan av de olika parametrarna, dvs luftfuktighet, lufttemperatur och luftfuktighet, på uppvärmningstid för olika

produkter, vattenförluster i produktens och ytans utseende, dvs hur stekskorpan ser ut. Även olika produktgeometrier skall studeras. I detta sammanhang planeras även receptstudier och studier av stekfettets inverkan på stekytan och stekytans bildande. Inverkan av stekningen på näringsvärdet kommer även att undersökas.

Den andra delen kommer att omfatta mer teoretiska beräkningsmoment. Här skall värmeöverföring från luft till yta och dess samband med stekskorpans bildande studeras. Luftfuktighetens betydelse kommer att undersökas. Dessutom kommer även värmetransporten inuti produkten att studeras. Som en orienterande förundersökning genomfördes hösten 1975 ett examensarbete. Där undersöktes köttfärsprodukters temperaturledningstal vid olika temperaturer i köttet vid tre olika lufttemperaturer, tre olika hastigheter och tre olika fuktigheter. Dessutom registrera-

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Quality Changes During Heating of Meat Products in a Convection Oven

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1.0 Introduction

In spite of the fact that the production of ready-to-serve foods increases rapidly and that people eat more and more meals outside their homes – in Sweden at least one per day – most of the methods for food preparation has not been changed very much. In order to be able to use modern engineering technique, one has to obtain the basic facts about the influence of different heating parameters on the quality of the product. It is very important that the food industry and the different catering units are serving food that is nutritious and welltasting, and that they at the same time are using the preparing processes in an optimal way.

There are four principally different ways of frying and heating meat products, that is deep fat frying, infrared radiation, pan frying and forced convection.

In our investigation we have used a forced convection oven. That means that the product is exposed to heated circulating air. A commercial convection oven consists of an oven space with a fan placed in one of the walls. The air passes through the fan and the heating elements and is then circulated in the oven. Originally forced convection ovens were used as baking ovens. The purpose of circulating the air is to blow in steam or water, in order to prevent the product from drying and to speed up the heating time a little further.

At the institute in Alnarp, Sweden, a convection oven for investigation purposes was constructed and built like a wind tunnel (figure 1) with possibilities to reverse the air flow. The oven space (figure 2) has the dimensions $325 \times 325 \times 340$ mm and has three shelves, where products can be placed [1, 2].

The intentions when constructing the oven was that one should be able to control air temperature, air velocity and air humidity, thus controlling the heating or frying process very carefully. Control devices for these three parameters are placed in the oven space.

Air velocity is controlled by a pitot tube, the air temperature by a thermocouple and the humidity by an especially designed unit made at the institute [3].

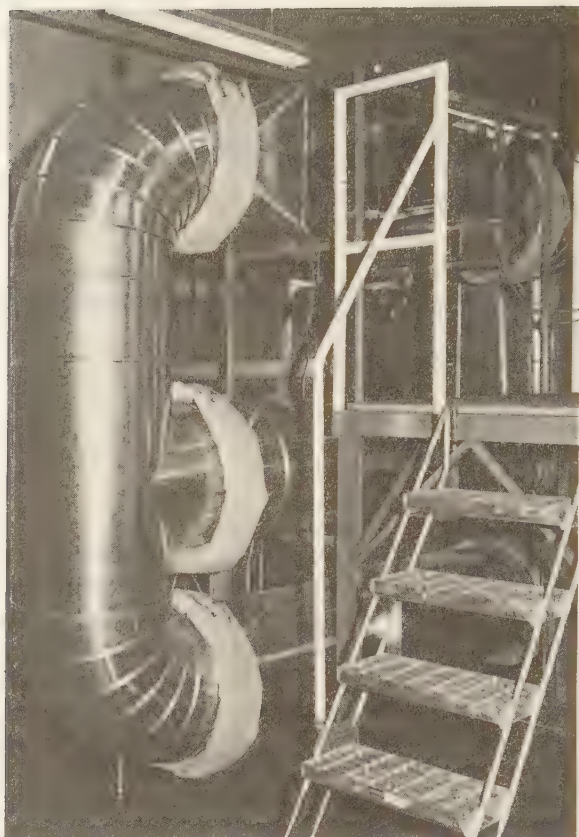


Figure 1. The convection oven built at the institute in Lund.

All temperatures, humidity and velocity values pass a datalogger and are registered on a punched tape for later computer evaluation. The air velocity can be varied between 1–12 m/s and air temperature between 20–400°C. Steam or water can be added to humidify the air before it reaches the fan. The fan is placed prior to the heating elements, which have an effect of 15 kW. Air humidity can be varied between 0–1 kg water/kg humid air.

The goal of the investigation is to obtain an optimal way for frying a minced meat product in a convection oven. Observations made are time, weight losses, thiamine retention, colour and sensorial analysis of taste, colour, juiciness, consistency and appearance.



Figure 2. Detail from the oven space.

2 Methods and Result

2.1 Methods

2.1.1 Frying Procedure

Minced meat of a recipe used in industrial processing was formed to a loaf, $20 \times 5 \times 5$ cm, and was placed in a teflon-coated net cage to avoid change of shape during frying (figure 3).

Two thermocouples (chromel-alumel) were inserted to the middle from the short side of the meat loaf, one in the centre and one half-way between the centre and the surface. Due to the shape of the loaf the temperature changes in the middle part are influenced only by heat transfer from the long sides. This simplifies calculations made on the thermal process in this region.

The frying was conducted until the temperature in the centre reached 70°C . The meat loaf was removed from the oven and after three minutes it was weighed and frozen in an ethanol-dry ice bath for further analysis.

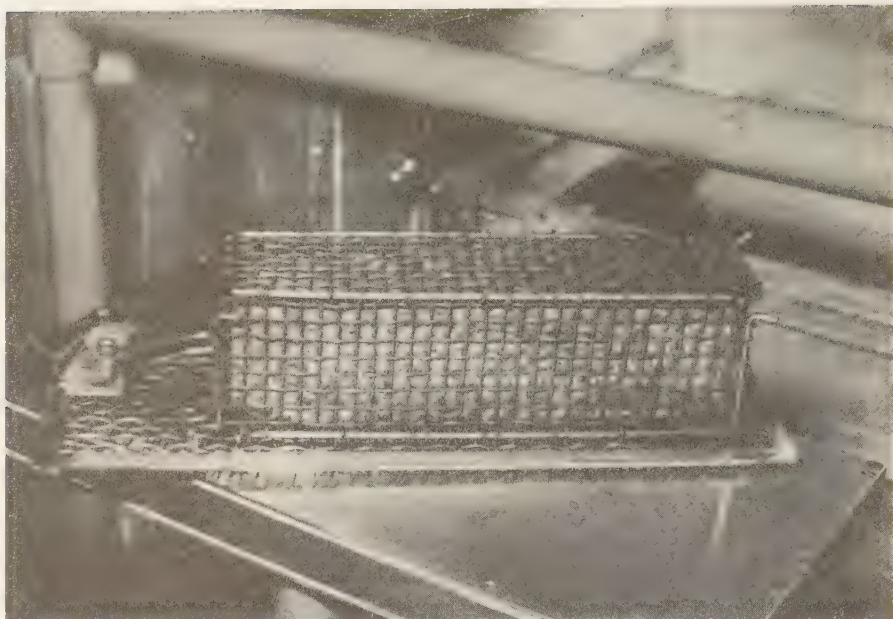


Figure 3. The minced meat loaf in its net cage.

2.1.2 Frying Conditions

Fryings were performed with the different set of parameters according to table I, and as a reference frying took place in an ordinary kitchen oven at 225°C thus without convection. At each specific set four individual fryings were accomplished.

Table I. Frying conditions.

Air temperature	150, 225, 300	°C
Air velocity	3, 5, 7, 9	m/s
Air humidity	0, 1.3	kg H ₂ O/kg dry air

2.1.3 Analysis

Weight changes were measured by weighing the whole meat loaf before and after frying.

One meat loaf fried at one set of parameters was taken out for sensorial analysis. The thiamine contents were analysed according to the method described by the Association of Vitamin Chemists [4]. A 1 cm thick slice was cut out from the middle of the meat loaf and homogenized. From the homogenate three individual samples were assayed simultaneously with three samples from homogenized raw meat to determine the thiamine retention associated with each process.

2.2 Results

2.2.1 Frying Time

Time-temperature plots were made for each parameter and the frying-time was calculated as the time it took the centre of the product to reach 70°C. Table II shows the frying time and its variation with air temperature, humidity and air velocity. In figure 4 frying time is plotted against air velocity and air temperature. The diagrams to the left represent frying when air is dry and those to the right frying when the air contains 1,3 kg water/kg dry air.

Table II and figure 4 show that frying time varied between about 20 and 45 minutes and that air humidity had great influence only at low air temperatures. Air velocity had influences mostly at 150°C and dry air.

It seems that air velocity and air temperature had very little effect on frying time at high temperatures and at low temperatures when air humidity is high. At these values, where the variations are small, the heat transport is obviously not controlled by the heat transfer between air and product, but in the product itself.

The variance of each value was drawn in the diagrammes.

As a reference the meat product was also fried in an ordinary kitchen oven at 225°C without forced convection. The frying time was found to be very high compared to the time needed in the convection oven at the same temperature.

2.2.2 Weight Losses

The meat was weighed before and after frying (to 70°C in the thermal centre) and the weight losses were calculated in percent of the raw weight. Table III shows the

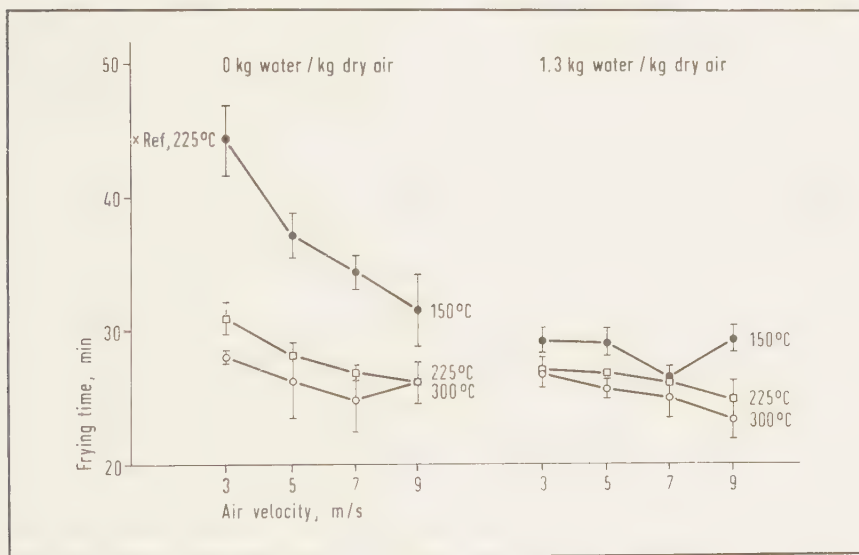


Figure 4. Frying time

Table II. Frying time in minutes (mean value of 4 samples).

Air temperature °C		150		225		300	
Air humidity kg water/kg dry air		0	1.3	0	1.3	0	1.3
Air velocity m/s	3	44.7	29.0	30.9	27.0	28.0	26.7
	5	37.3	29.2	27.9	26.7	26.0	25.4
	7	34.4	20.3	26.6	26.1	24.5	24.9
	9	31.5	29.4	26.0	24.7	26.0	23.1
Reference				44.6			

Table III. Total weight losses in % of the raw weight (mean value of 4 samples).

Air temperature °C		150		225		300	
Air humidity kg water/kg dry air		0	1.3	0	1.3	0	1.3
Air velocity m/s	3	6.4	3.8	10.9	10.0	17.8	16.1
	5	6.7	5.1	13.3	12.9	19.1	17.7
	7	7.7	4.9	13.8	13.5	19.6	19.1
	9	8.1	6.3	15.0	14.4	22.7	18.6
Reference				8.1			

Table IV. Weight loss per time (mean value of 4 samples) in %/min.

Air temperature °C		150		225		300	
Air humidity kg water/kg dry air		0	1.3	0	1.3	0	1.3
Air velocity m/s	3	0.1	0.1	0.4	0.4	0.6	0.6
	5	0.2	0.2	0.5	0.5	0.7	0.7
	7	0.2	0.2	0.5	0.5	0.8	0.8
	9	0.3	0.2	0.6	0.6	0.9	0.8
Reference				0.2			

weight losses, which range from 3% to 25%. This means that the meat loses up to 1/4 of the weight. The weight losses depend not only on air flow parameters, but also on the recipe.

Table IV shows the variation when the weight losses are divided by frying time and these values range from 0.1 %/min to 0.9 %/min.

Figure 5 shows the total weight losses as a function of air velocity and air temperature. Figure 6 shows weight losses/min as a function of air velocity and air temperature.

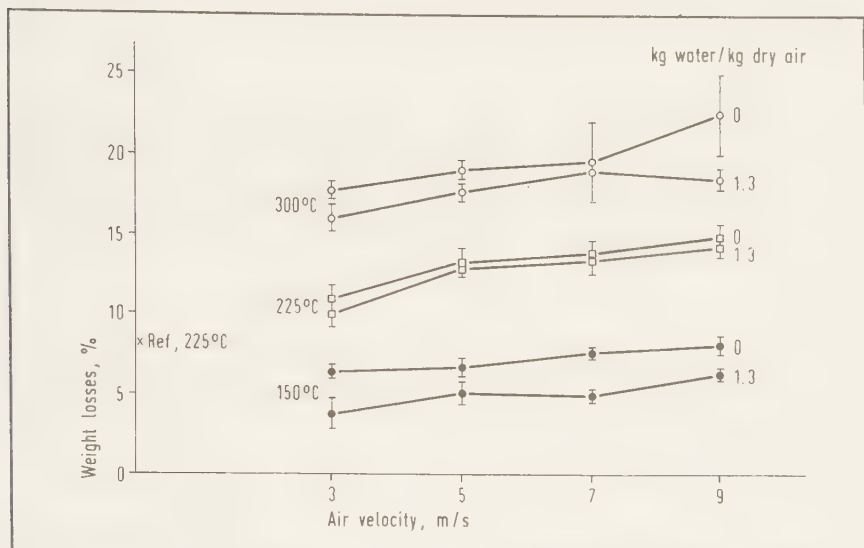


Figure 5. Weight losses

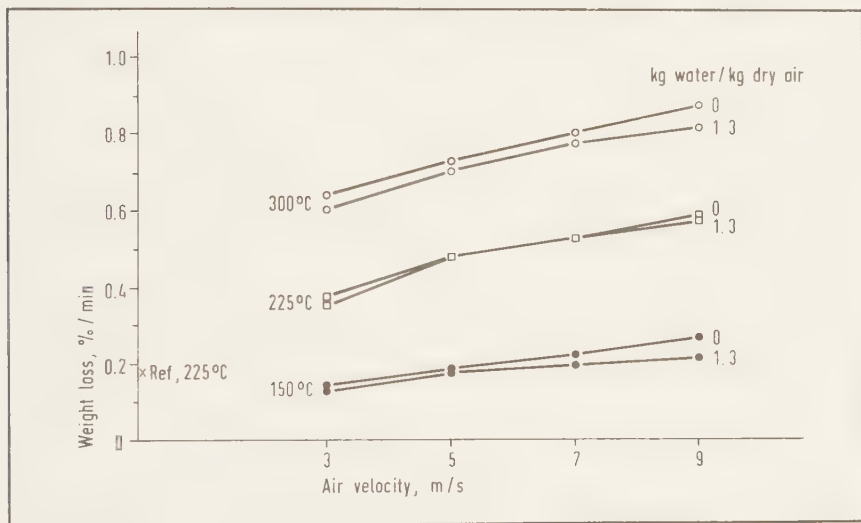


Figure 6. Weight losses/time

Figure 5 shows that the air temperature has great influence on weight losses, air humidity has influence only at low temperatures, and air velocity has a small influence only. For example the weight loss at 225°C and 3 m/s is 10% and at 9 m/s it is 15%. That means an increase of 50%.

From figure 6 it can be seen that the difference in weight losses/min, depending on air humidity, at 150°C has shrunk at least at low air velocity.

One interesting thing is that the reference has only lost 8% in spite of the long time, 45 minutes.

2.2.3 Thiamine Retention

Table V shows the thiamine retention after frying. This value shows the amount of thiamine left in the sample after frying as a percentage of the total amount. The sample for analysis was a cross section of the meat loaf which was homogenized. This means that the value obtained was a mean value from meat with different temperature story.

Table V. Thiamine retention in % of the total amount in the raw meat (the values are calculated on wet basis).

Air temperature °C		150		225		300	
Air humidity kg water/kg dry air		0	1.3	0	1.3	0	1.3
Air velocity m/s	3	85.6	100.0	93.7	97.4	71.0	78.7
	5	96.0	92.6	92.5	90.0	68.5	65.7
	7	91.3	94.7	81.3	87.1	57.8	58.8
	9	92.5	90.4	83.7	83.0	64.2	52.2
Reference				93.8			

In figure 7 these values were plotted as a function of air velocity and temperature. The thiamine retention is comparatively low when air temperature is 300°C, especially at high air velocities. A small change in air velocity changes the thiamine retention drastically.

At lower air temperatures change in air velocity seemed to have greater influence than the temperature itself. At 150 and 225°C the thiamine retention was much higher than at 300°C. The air humidity does not seem to have any noticeable influence.

The reference sample at 225°C had relatively much thiamine left in spite of the long time. It retained the same amount as the sample fried at the same temperature at 3 m/s. Presumably the air temperature is not the real parameter for thiamine retention obtained at our investigation but an integral of time, temperature and volume.

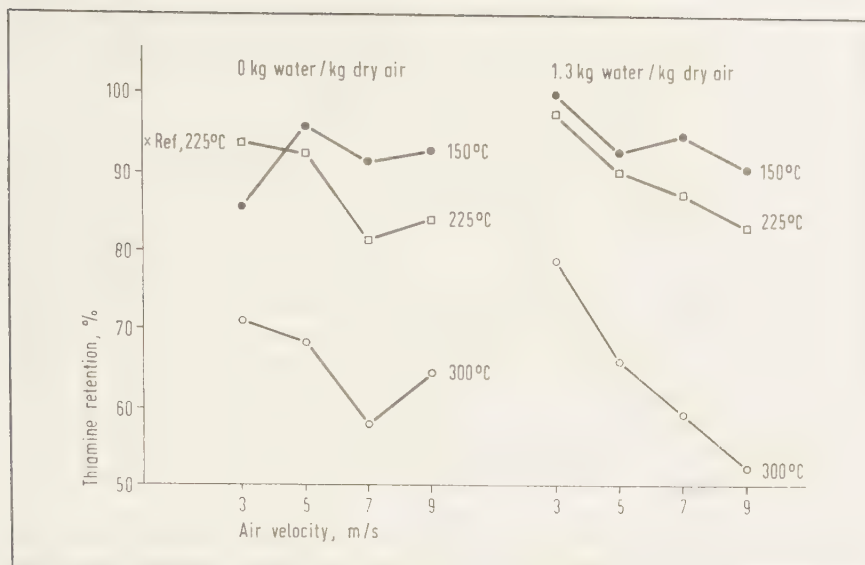


Figure 7. Thiamine retention.

3.0 Summary

The paper reports studies of physical properties and thiamine retention in minced meat samples when fried in convection ovens. When frying this type of product, air humidity seems to have influence on frying times and weight losses only at low temperatures and no influence on thiamine retention.

Air velocity had a notable effect on frying time at low and on weight losses at all temperatures. The frying time seemed to decrease and the weight losses increase at an increase in velocity. The air velocity had a great influence on thiamine retention at high temperatures, but also, to a certain extent, at lower temperatures. At 300°C the thiamine retention decreased very rapidly when the air velocity was increased. Air temperature had influence on frying time, weight losses and thiamine retention. When rising the air temperature from 150°C to 225°C the weight losses increased almost as much as when the temperature was increased from 225°C up to 300°C. The influence on thiamine retention was very distinct when the air temperature was risen from 225°C up to 300°C. The conclusion is that at 300°C frying time was not very much shorter than at 225°C, but vitamin retention was remarkably lower and weight losses were high. This investigation shows that to obtain the best thiamine retention, minimum weight loss and minimum frying time, 150°C, high air humidity and an air velocity between 3 and 9 m/s should be used. However, to obtain an optimal way of frying in a convection oven one also has to consider the sensorial

properties (appearance and the taste). These will be investigated, and that will probably change the optimal values of the variables.

Résumé

Les méthodes les plus usuelles, par lesquelles on transmet la chaleur aux denrées alimentaires sont ou la conduction, p.e. dans la poêle, ou les rayons infra-rouges, ou la convection forcée, p.e. dans les fours à convection. Dans la recherche présente la convection forcée a été utilisée. On a fait une brique de viande hâchée de $20 \times 5 \times 5$ cm, et l'a traitée à la chaleur dans un four à convection construit à ce dessein. On a examiné l'influence de la température de l'air, celle de son humidité et celle de sa vitesse de circulation sur le temps de cuisson, sur la perte de poids, sur la couleur, et sur la conservation des vitamines. La température de l'air (150, 125 et 300 °C) et la température du produit (30 et 90 °C) étaient réglées avec une tolérance de 1 °C, et la vitesse de l'air était réglée à 3, 5, 7 et 9 m/sec.

Les changements de températures dans la viande étaient constamment surveillés. Chaque fois que la température au centre du produit arrivait à 70 °C, le réchauffage a été interrompu et le produit pese. Deux spécimens ont été extraits du centre du produit, à l'aide desquels on déterminait le contenu en eau, en graisse et en thiamine.

Zusammenfassung

Die gebräuchlichsten Arten der Wärmeübertragung auf Lebensmittel sind entweder Konduktion wie bei Bratpfannen und Infrarotstrahlen, und erzwungene Konvektion wie in Konvektionsöfen. In der vorliegenden Untersuchung wurde erzwungene Konvektion als Mittel der Wärmeübertragung angewendet.

Hackfleisch, das in Form eines Quaders mit einer Länge von 20 cm, einer Breite von 5 cm und einer Höhe von 5 cm gebracht worden war, wurde in einem speziell ausgerüsteten Konvektionsofen hitzebehandelt und der Einfluß verschiedener Lufttemperaturen, Feuchtigkeiten sowie Luftgeschwindigkeiten auf Bratzeit, Gewichtsverlust, Farbe der Oberfläche und Vitaminerhaltung des Fleisches untersucht. Die Lufttemperatur im Ofen (150, 125 und 300 °C) sowie die Feuchttemperatur (30 und 90 °C) wurden innerhalb von 1 °C konstant gehalten, die Luftgeschwindigkeit betrug 3, 5, 7 und 9 m/s.

Die Temperatur in der Probe wurde laufend verfolgt. Sobald eine Kerntemperatur von 70 °C erreicht war, wurde die Heizung abgeschaltet und das Produkt gewogen. 2 Proben aus der Mitte des Fleischquaders dienten zur Bestimmung des Wasser-, Fett- und Thiamingehaltes.

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SOME ASPECT ON FRYING OF MEAT PRODUCTS IN A FORCED CONVECTION OVEN.

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Introduction

During the last decades there has been a strong tendency towards eating food prepared in the Food Industry and/or in different catering units. In Sweden today (1978) about 4 million meals are served outside the home. It is therefore important to prepare well tasting and nutritious food and at the same time optimize the preparation processes. One of the most useful apparatus in the canteens, is the forced convection oven. In this the product is exposed to circulating hot air. A commercial oven consists of an oven space with a fan placed in one of the walls. The air passes through the fan and the heating elements and is circulated in the oven.

One reason why the convection oven is so useful, is its many applications. It may, among other things, be used for frying, cooking, reheating, thawing and warm-holding of many geometries of foods.

The aim of this investigation is to find the optimal combinations of process parameters, when frying minced meat products in a convection oven. This report is one part of a greater project, where the applications of these types of ovens have been studied with regard to optimization. Observations reported in this investigation are frying time, weight losses, thiamine retention, colour and sensorial properties of taste, juiciness and appearance.

The first part of this investigations has been published earlier (1). Frying time, weight losses and thiamine retention are presented. In this second part sensorial properties, colour of the crust and some supplementary analysis were accounted for.

Material and methods

1. Oven design and samples

Dagerskog and Sörenfors (2) made an investigation to comparing four different methods of frying meat patties. Due to comparatively low heat transfer coefficients when frying in convection ovens the oven temperature had to be very high when frying this type and size of products. The reason is, that it is difficult to get an acceptable crust in combination with low enough temperature in the center at low oven temperature. The frying time is too short. Due to this bigger meatloaves with the dimensions 20 x 5 x 5 cm were chosen for the present investigation.

The recipe was one used in industrial processing, similar to that used in the above mentioned investigation.

The same convection oven as before was used (1). This oven is especially designed for investigation purposes.

2. Experimental procedure.

Frying was conducted until the temperature in the centre of the meat loaf reached 70°C. The loaf was immediately removed from the oven and after three minutes in room temperature it was weighed and then kept frozen (-40°C) for further analysis. Frying was performed with the different set of parameters according to table 1. As a reference loaves, fried in a kitchen oven without convection at 225°C were used.

Table 1.

Air temperature	150	225	300 °C
Air velocity	3, 5, 7, 9		m/s
Air humidity	0		1.3 kg H ₂ O/kg dry air

The meat loaves were reheated to eating temperature in an ordinary convection oven. As reference loaves fried in an industrial process were taken. Five trained judges from a food industry were used.

The crust colour was measured as brightness. An Elrepho-Colour Measurement unit was used. For calibration, the common permanent calibration standards were used. The brightness values presented are defined according to DIN-standard.

Results

1. Composition of weight losses

The total weight losses resulting from the different processing conditions, were reported earlier (1) and are summarized in table 2. The composition of the losses were analysed on some of the samples and are presented in table 3.

The samples fried at low temperature (150°C), showed minor total losses inspite of the long frying times. This loss was almost exclusively water. The samples fried at higher temperature suffered a considerably larger total weight loss. This loss still consisted mainly of water, however, with a somewhat increasing amount of fat. Only minor protein losses could be detected.

2. Colour measurements

The brightness of the crust was measured in the Elrepho Colour Measurement Unit three minutes after frying. Diagramme 1 shows the brightness in percent as a function of velocity at different air humidities and temperatures. A dark samples gives a low figure. Air temperature seemed to have great influence on the crust colour. At 150°C , air velocity had greater effect when the air was dry than at high humidities. At 300°C air humidity and velocity seemed to have no effect. According to earlier investigations the brightness should be between 10 and 15 percent to be acceptable for this type of recipe (2).

This means that all sample fried at 300°C were too dark. Among those samples fried at 225°C , the crusts were acceptable at 3 m/s and 5 m/s. At 150°C , all those fried in humid air were too bright but those fried in dry air, 7 and 9 m/s, were acceptable.

3. Sensoric properties.

The total impression of appearance and taste were tested as well as intensity of juiciness. All judgements are related to the reference. The score for this is drawn in the diagrams. Diagramme 2 shows the juiciness as a function of air velocity, air temperature and air humidity. The air conditions chosen did not influence the juiciness of the product in any degree.

Diagramme 3 shows the total impression of appearance. When frying at 150°C and dry air the product seemed to look very good as well as at 150°C , 9 m/s and humid air, compared to the reference.

Diagramme 4 shows the total impression of taste as a function of air velocity at different air temperature and air humidity. Frying at 150°C and 225°C and humid air seemed to give a well tasting product, as well as at 150°C , 9 m/s, 5 m/s or 3 m/s and dry air, compared to the reference.

Statistically the following results were given.

1. The intensity of juiciness showed no significant differences at all with any air condition.
2. Total impression of appearance
 - a) There was significant differences when changing the velocities, at the level of 95 %, at 150°C and 225°C and dry air.
 - b) There was significant differences between temperatures, at the level of 95 % at 5 m/s and 9 m/s at dry air.

- c) At the level of 95 %, there was a significant difference between temperatures at 3 m/s and 9 m/s when the air was humid.
- d) At 300°C and humid air, there was a significant difference at the level of 95 % when changing the velocities.

3. Total impression of taste

- a) There was a significant difference, when changing the velocities, at the level of 95 %, at 150°C and 225°C and dry air.
- b) There was significant differences between temperatures, at the level of 95 %, at 5 m/s and 9 m/s and dry air.
- c) There was significant differences between temperatures, at the level of 95 %, when the air was humid.

This means that the taste was better when frying in a low air temperature. The air humidity had no effect on appearance or taste at the same air velocity. The air velocity had an effect on taste at 150°C and 225°C and dry air.

4. Frying time

Table 4 shows the frying time as a function of air velocity at different air temperature and humidity (1).

5. Thiamin retention

Table 5 shows the thiamin retention as a function of air velocity at different air temperatures and humidities (1).

Discussion

Table 4 shows that only at the air temperature 150°C with dry air, is the air velocity of practical importance for the frying time. At all the other frying conditions, the frying time was approximately equal. The weight losses, on the other hand, differ as shown in table 3. The explanation for this could be, that the energy needed to get the product fried is

partly used for rising the temperature and partly for evaporating water. When the surface has reached 100°C and the crust formation has started the air conditions will have little influence on the remaining frying time. The heat transport inside the product is proportional to the temperature gradient. To increase this gradient, the 100°C isotherm has to be moved towards the center of the product. This movement is related to the crust formation. Additional energy transferred from the air is used for evaporating the water and for heating the crust. At 150°C , low air velocities and dry air, it takes a long time to accumulate enough energy to heat the surface to 100°C and from the crust. The weight losses consist of evaporated water and "drip" due to changes in water holding capacity of the product. (3). When the muscle proteins are coagulated at temperatures between $30\text{--}50^{\circ}\text{C}$ they lose considerable amounts of water. (6). For pure meat these losses could be great and are measured as "drip". In this investigation we have used in the recipe apart from minced meat a mixture of ingredients which have abilities to absorb water. The losses due to drip therefore are of minor importance. This is confirmed by the low weight losses obtained at 150°C 3 m/s and dry air. The lack of change in juiciness is probably also due to this fact.

There was an evident tendency that . . . air temperature, air velocity and in some cases air humidity had influence on colour, taste and appearance.

Diagramme 5 shows that there is an evident tendency that the darker a product is the greater are the total weight losses independent of air condition. This indicates that surplus energy, above that determined by internal heat transport forms the crust. The colour of the product should have an effect on the appearance. Diagramme 6 shows that there could be a slight maximum between 10 and 16 % brightness which is in agreement with results from earlier investigations. (2). At the same time, there is a slight tendency towards better scores in appearance the less . . . the total weight losses are at least so some extent (Diagramme 7). When looking at the

taste there seems to be a better score when there are small weight losses and at a brightness around 15 % (Diagramme 8 and 9). Diagramme 10 shows that there was no connection between vitamin retention and taste. Table 6 shows the linear correlation coefficient for the different properties and at what level there was a significant tendency of dependence between these properties (5).

It is difficult to decide what quality property is most important, when optimizing the frying process. In this investigation, as said before frying time, total weight loss, thiamine retention, taste, appearance, juiciness and crust colour were analysed in the product fried until the center reached 70°C. Looking at each property, frying time and total weight losses should be kept low and at the same time thiamine retention should be high. Also the sensorial properties should have high judgement scores together with an acceptable crust colour. If all these properties are given the same importance, the minced meat loaf should be fried at a low air temperature and high air humidity or at high velocity (dry air). At high air humidity, however, the crust colour is too bright referring to the recommendation that the brightness should be between 10 and 15 %.

(2). Diagramme 5-10 and table 6 show that some properties measured in this investigation are dependent of each other. A change in weight losses or colour does not change the score for taste very much and the thiamine retention has no correlation at all with taste. A change in colour changes the weight losses and the higher the air temperature is, the greater is the weight losses. For optimization the above mentioned facts could be of help.

These facts, together with the recommendation that the brightness should be between 10 and 15 give the results that the best frying conditions are a low air temperature together with high air velocity and dry air for this type of product.

This investigation shows that

- 1) The air conditions does not influence the frying time at higher air temperatures

- 2) The frying time is decreasing with decreasing air velocities at low air temperatures.
- 3) Air humidity increase the frying time at low air temperatures and low air velocities.
- 4) The weight losses and the crust colour are dependent on the air temperature.
- 5) The impression of taste and appearance are dependent of the crust colour.
- 6) The best score for appearance of the meat loaf is between 10 % and 16 % brightness.
- 7) For further investigations the most optimal conditions when frying meat loaves, were chosen as 150°C, dry air and 9 m/s.

Acknowledgements.

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Table 2.

Total weight losses in % of the raw weight (mean value of 4 samples).

Air temperature(°C)	150		225		300	
Air humidity (kg H ₂ O/kg dry)	0 ;	1.3 ;	0 ;	1.3 ;	0 ;	1.3
Air velocity (m/s)						
3	6.4	3.8	10.9	10.0	17.8	16.1
5	6.7	5.1	13.3	12.9	19.1	17.7
7	7.7	4.9	13.8	13.5	19.6	19.1
9	8.1	6.3	15.0	14.4	22.7	18.6
Reference	8.1					

Table 3.

Composition of the weight loss

Sample Frying parameters			Frying time (min)	Total loss (% of raw weight)	Composition of the loss (% of total loss)		
Temp (°C)	Air humidity (kg H ₂ O/kg/ dry air)	Air velocity (m/s)			Water	Fat	Protein
150	0	3	44.7	6.4	> 97	< 3	
150	0	9	31.5	8.1	> 97	< 3	
225	1.3	3	27.0	10.0	95	5	
225	0	7	26.6	13.8	95	5	
300	1.3	9	23.1	18.6	85	10	2.5

Composition of raw meat:

Water: 63 %

Fat: 13.7 %

Protein 10.7 %

Table 4.

Frying time in minutes (mean value of 4 samples)

Air temperature (°C)		150		225		300	
Air humidity (kg water/kg dry air)		0 1.3		0 1.3		0 1.3	
Air velocity (m/s)	3	44.7	29.0	30.9	27.0	28.0	26.7
	5	37.3	29.2	27.9	26.7	26.0	25.4
	7	34.4	26.3	26.6	26.1	24.5	24.9
	9	31.5	29.4	26.0	24.7	26.0	23.1
	Reference			46.6			

Table 5.

Thiamine retention in % of the total amount in the raw meat (the values are calculated on dry basis). Mean value of 4 samples.

Air temperature (°C)		150		225		300	
Air humidity (kg water/kg dry air)		0 1.3		0 1.3		0 1.3	
Air velocity (m/s)	3	86.4	102.8	81.6	87.0	59.1	67.3
	5	87.2	84.5	78.2	76.5	57.5	55.3
	7	82.2	84.0	70.6	75.9	47.4	48.4
	9	76.7	84.3	70.4	68.5	53.2	44.6
Reference				80.4			

Table 6. Linear correlation coefficients.

	r	α
Appearance vs:		
Colour	+ 0.72	0.01
Weight losses	- 0.68	0.01
Taste vs:		
Colour	+ 0.58	0.01
Weight losses	- 0.59	0.005
Colour vs:		
Weight losses	- 0.97	0.01
Thiamine retention vs:		
Taste	+ 0.28	-

* $P < 0.05$ $r = 0.423$ ** $P < 0.01$ $r = 0.537$

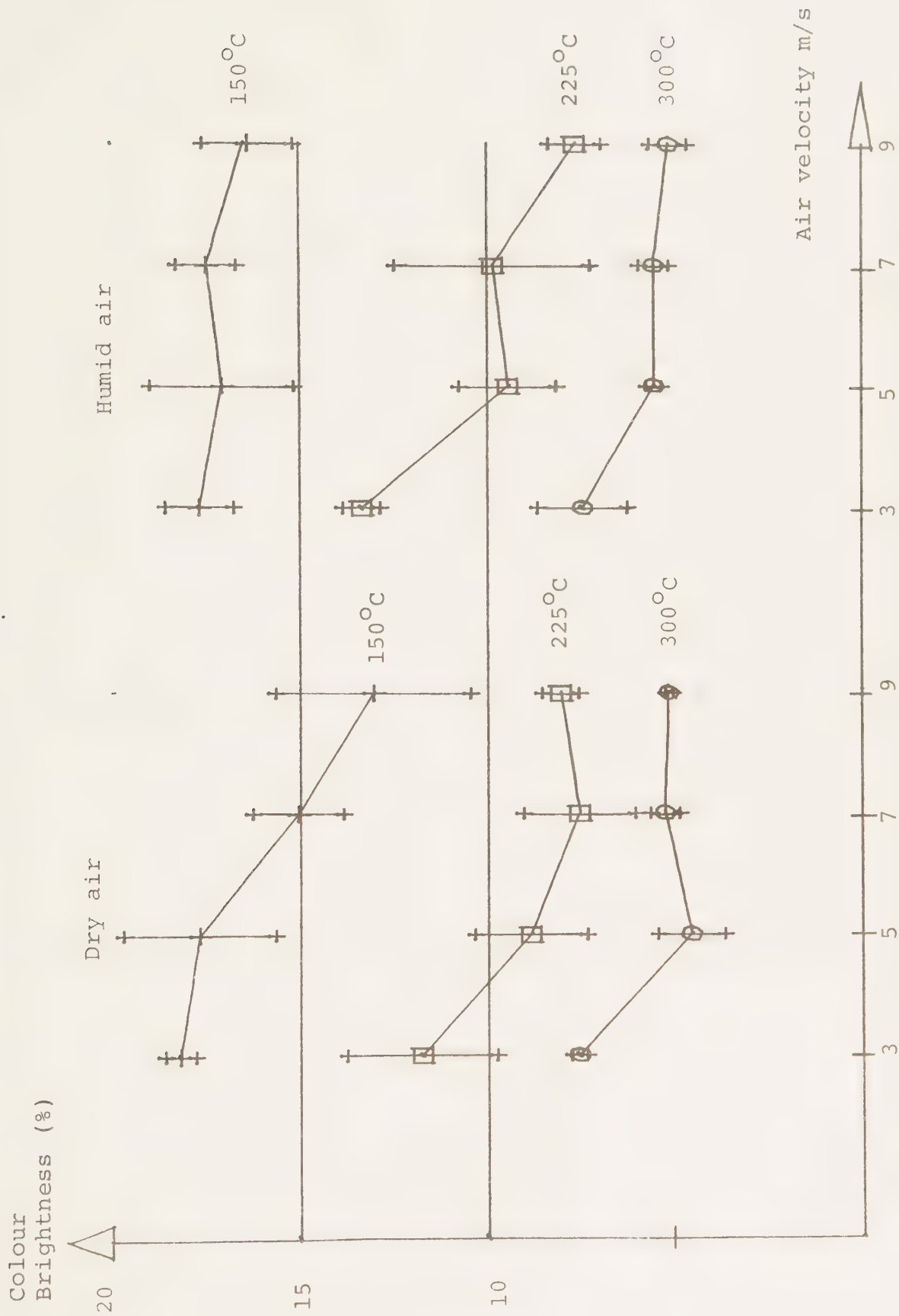
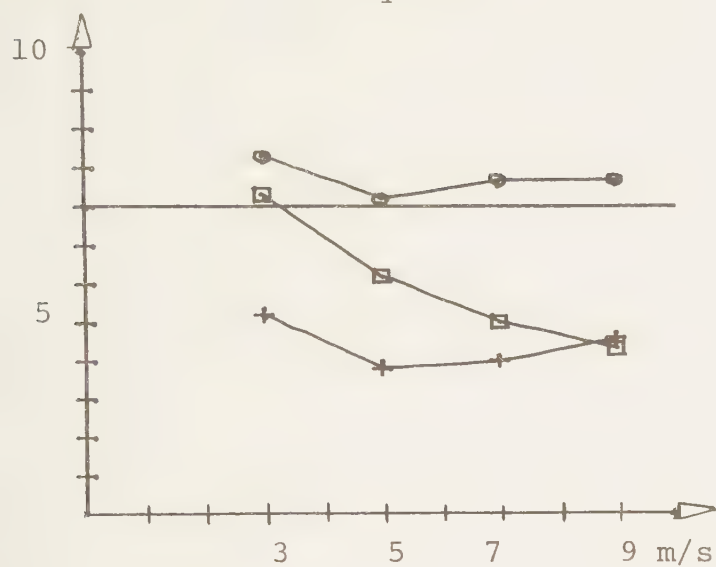
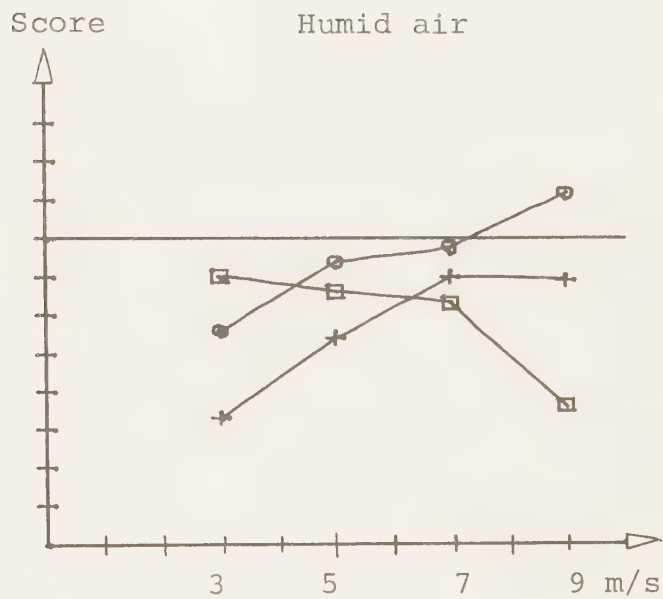


Diagramme 1. Colour of the crust as a function of air velocity at different air temperatures and air humidities

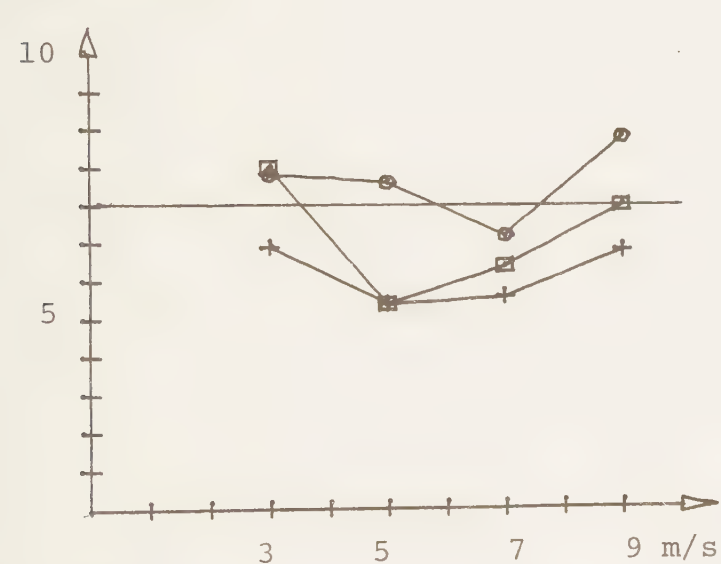
Appearance
score



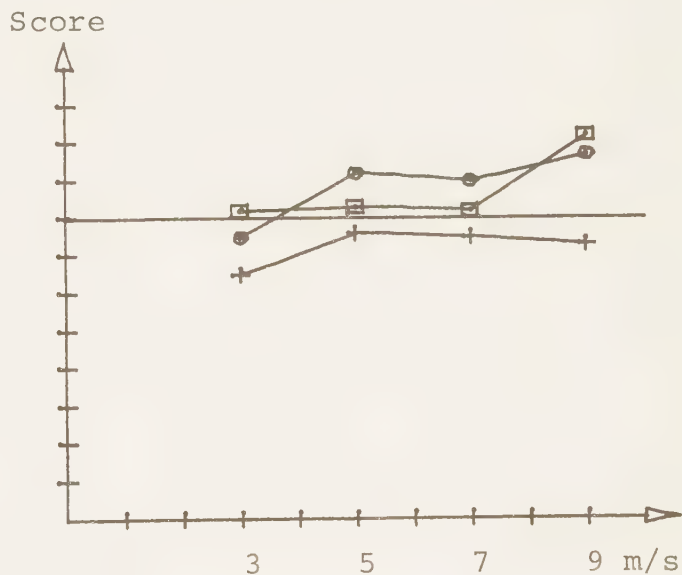
Score



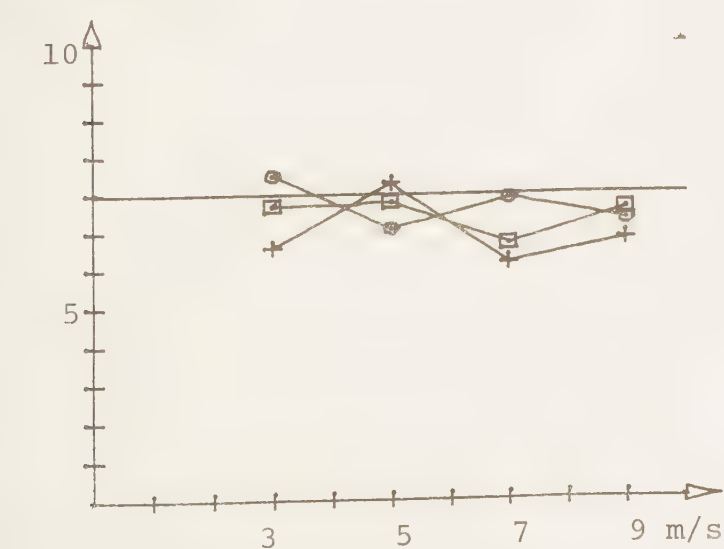
Taste score



Score



Uiciness score



Score

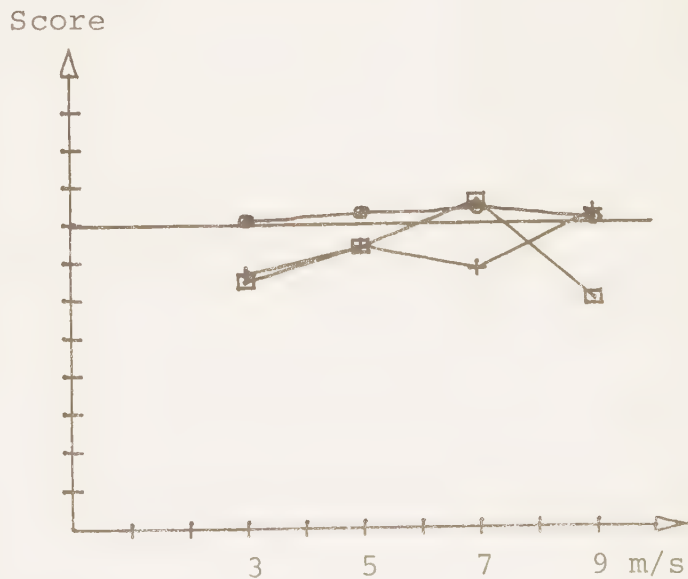


Diagramme 2,3,4. Judged scores of sensoric quality as a function of air velocity at different air temperatures and air humidities o 150°C □ 225°C + 300°C.



Diagramme 5. Colour of the crust as a function of weight losses.

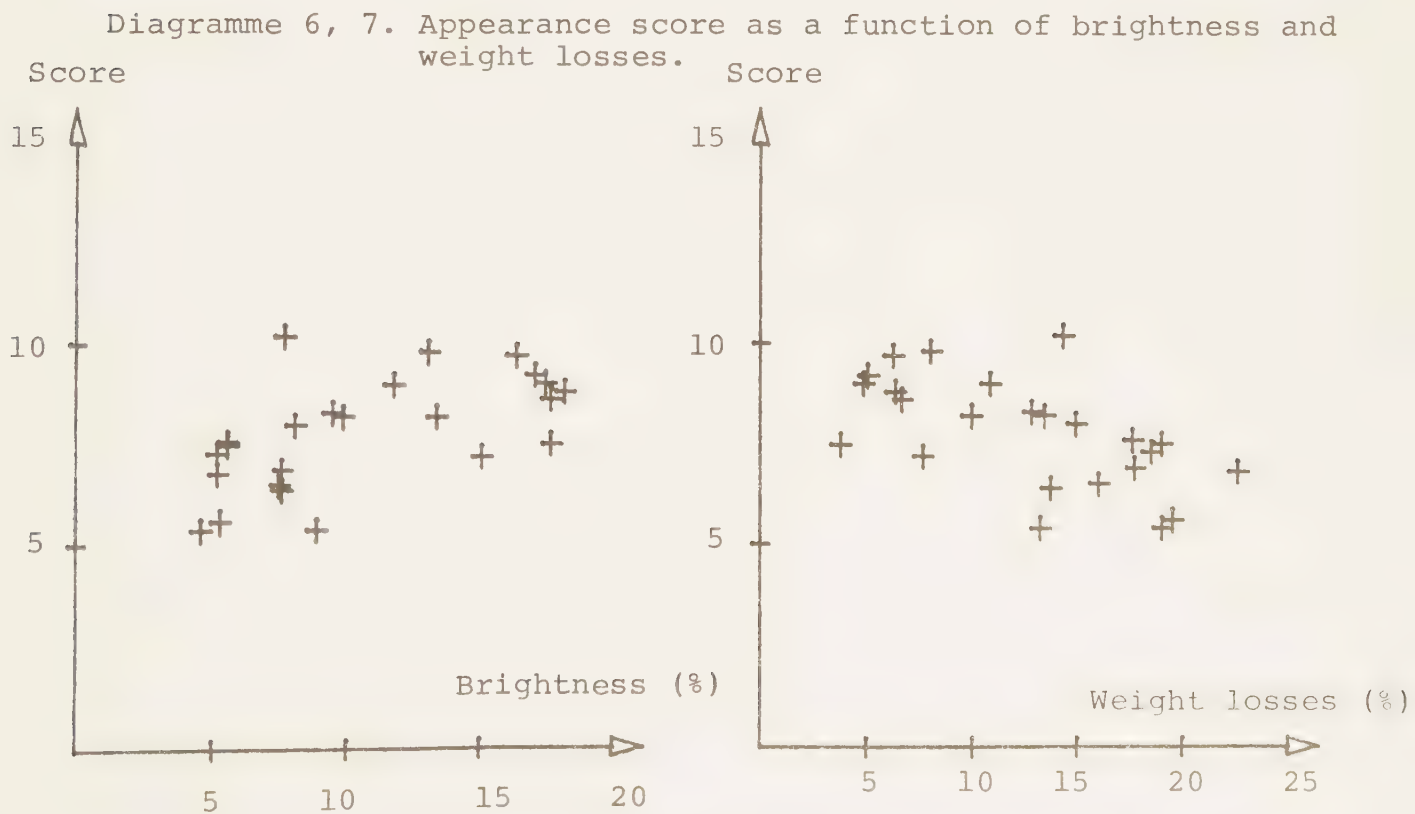




Diagramme 10. Thiamine retention as a function of taste score.

Reheating of minced meat products in a convection oven.

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Introduction

In Sweden the quantity of ready-to-serve foods are growing and people very often eat at least one meal a day outside their homes. These meals are often served during a very short period of the day. The food has to be prepared and then kept warm for a long time, which may lead to reduced palatability and nutritional value (1). One alternative procedure involves freezing of pre-fabricated meals which are thawed and reheated when the customer asks for the meal. This requires equipment to reheat the food fast, at the same time retains its nutritional value and food tastes. Furthermore the operators must have knowledge about how to handle both the equipment and the product.

Investigations were made on reheating food in different types of equipment (2). One of the most useful apparatus is the convection oven. Different types of commercial convection ovens have been examined (3, 4, 5). A lot of products have been tested, mostly in packages. The reheating time can be reduced, for example, by increasing the temperature difference between the heating medium and the product, increasing air velocity or reducing the thickness of the food layer. There are, however, some limitations due to the temperature tolerance of the food (6).

As a step in an effort to understand convection oven heating of ready-to-eat foods this investigation was made. Earlier, frying of meat products in a research convection oven was surveyed (7, 8). Conclusions made from that investigation was that low air temperature combined with high air velocity gave the best results with regard to thiamine retention, frying time, weight losses, colour and sensorial properties.

Starting from the earlier investigation (7, 8), reheating of the same type of product was examined. The aim of the investigation was to understand how the air parameters effect the reheating process. Temperature, humidity and velocity of the air were varied. The heating time, weight losses, colour changes, thiamine retention and the sensorial properties taste, smell and appearance were measured.

Material and Methods.

Convection oven design and product sample.

The apparatus used was a convection oven made for research purposes; fig 1. It was built like a wind tunnel in which it was possible to reverse the air. The air was dispersed, with the aid of guide plates and finely meshed netting, over the oven cavity. This had the dimensions 325 x 325 x 325 mm and had three shelves for the product. Temperature and velocity of the air were controlled. The humidity was measure by a specially designed equipment (8, 9). The air temperature could be varied between 20-400°C, the humidity from completely dry air to pure steam and the air velocity between 2-12 m/s. Chromel-alumel thermocouples were used for measuring temperatures in the product and an IR-sensing head measured the surface temperature on the product. All temperatures,

humidity- and velocity values passed a datalogger and were recorded on a punched tape for further computer evaluation.

The type of minced meat used was the same as the one (7, 8) in the earlier investigation. The meat was formed to a loaf with the dimensions 200 x 50 x 50 mm.

Experimental procedure.

Some of the meat loaves were fried at 9 m/s dry air at 150°C for 30 minutes which gave 70°C in the center. This combination of air parameters gives a good product as according to earlier studies (7, 8). The other part was "boiled" at 125°C 5 m/s humid air for 30 minutes. The rest of the loaves were "boiled" at 125°C 5 m/s humid was to see if it was possible to coagulate the meat with small weight losses. Not until reheating of these loaves the crust was formed.

The loaves were freezed and stored for 2,5 months. After thawing at +5°C for 12 hours, they were reheated according to table 1 and 2.

Table 1. Air parameters for reheating fried minced meat loaves.

Temperature	125	150	200 °C
Velocity	3 , 5 , 7 , 9 m/s		
Humidity	0	1.3 kg H ₂ O kg dry air	

Table 2. Air parameters for reheating "boiled" minced meat product.

Temperature	150	225	300 °C
Velocity	3 , 5 , 7 , 9 m/s		
Humidity	0	1.3 kg H ₂ O/kg dry air	

Heating was conducted until the temperature in the centre of the loaf reached 65°C. The temperature in the centre was followed continuously.

Analysis

The reheating time was calculated from the start until the centre reached 65°C.

Weight losses were determined by weighing the loaf before preparing, after preparing, after thawing and after reheating.

The colour of the crust was measured as brightness. An Elrepho-Colour Measurement unit was used. The brightness was measured after preparing, after thawing and after reheating.

The loaves were photographed and analysed for sensorial properties as follows:

1. Total impression of appearance (1 = very bad;
9 = very good)

Table 3. Results of the analysis after preparation and storage (Mean values of 48 samples). The thiamine retention was calculated on dry weight basis.

	Thiamine retention (%)		Weight losses (%)		Brightness (%)	
	Preparation	Storage	Preparation	Storage	Preparation	Storage
"Fried"	85.5	87.1	8.0±0.1	0.8±0.5	14.2±1.1	23.0±3
"Boiled"	97.0	96.3	2.4±1	1.9±1	20.7±1.5	29.1±1

The preparation time was 30 minutes. The products were stored in a freezer at -20°C for two and a half month.

2. Reheating time

Figure 2 and 3 shows the reheating time as a function of air velocity at different temperatures and humidities of the air. The necessary reheating time varied between 20 and 55 minutes.

3. Weight losses.

Figure 4 and 5 shows the weight losses during reheating procedure not including preparation and storage losses. Losses are plotted as a function of air velocity at different air temperatures and air humidities. The weight losses varied between 0 % and 25%

4. Colour measurements.

Figures 6 and 7 show the colour of the meat loaves after reheating. According to earlier investigations the acceptable brightness is between 10 and 15 % (11). The values vary between 15 % and 5 % depending on temperature and velocity.

5. Thiamine retention.

Figures 8 and 9 show the thiamine retention calculated on the content of the raw product and on the dry weight basis. The values ranged from 100 % down to 65 %.

6. Sensorial properties.

Figures 10, 11 and 12 show the sensorial properties as a function of air velocity. All judgements were referred to the reference meat loaf. The score for the reference was decided before the investigation started and was the same all through the sensorial tests. This reference score is shown in the diagrammes.

Statistical evaluations.

1. The total impression of appearance

a) Fried product

There was a significant difference, at the level of 0.01, between the air velocities at dry air 125°C. At 180°C and 200°C dry air there was no significant difference. There were significant differences at the level of 0.05, between air velocities at 125°C and humid air. However, at humid air 150°C and 200°C there was no significant difference between air velocities.

There was significant difference, at the level of 0.05, between the temperatures at 3 m/s and 5 m/s (dry air). 7 m/s and 9 m/s showed no significant difference.

There was no significant difference between temperatures at humid air.

b) "Boiled" product

There was significant difference, at the level of 0.05, between air velocities at dry air.

There were significant differences between temperatures at dry air and all velocities at the level of 0.001.

There was significant difference, at the level of 0.01 between air velocities at humid air.

There were no significant differences between temperatures at 5 m/s and 7 m/s and humid air. However, at the level of 0.05 there were significant differences at 3 m/s and 9 m/s.

2. The total impression of taste.

a) Fried product

There were no significant differences at all.

b) "Boiled" product

There were significant differences, at the level of 0.05, between the temperatures at dry air.

There were no significant differences between the air velocities at dry air.

There were no significant differences at humid air.

3. The total impression of smell

a) Fried product

There were significant differences between the air temperatures at 3 m/s dry air at the level of 0.01. At 5, 7, 9 m/s there were no significant differences.

There were no significant differences between the air velocities at dry air or at humid air.

There were no significant differences between the air temperatures at humid air.

b) "Boiled" product

There were no significant differences at all.

The "fried" product tasted and smelled significantly better than the "boiled" product. The "boiled" product still smelled and tasted boiled after reheating in spite of a nice coloured crust.

Discussion.

The results show that above a certain air temperature the reheating time was independent of air velocity, air temperature and air humidity. At temperatures below 200°C , however, it was possible to reduce the time considerably by increasing any of the air parameters. Thus when the air velocity was raised from 3 m/s to 9 m/s at 125°C the reheating time was reduced by 32 %. By elevating the temperature to 150°C it was reduced by 19 % and a further temperature rise to 200°C gave a reduction of the reheating time by 40 %. If air humidity was increased from 0 to 1.3 kg H_2O /kg humid air at 125°C and 3 m/s the time would be reduced by 55 %.

Reheating the "boiled" product gave considerably high weight losses. These losses increased with temperature and they were only partially decreased by using humid air. The reduction calculated in percent of total weight losses (including frying/boiling, storage and reheating) were around 20 % at 225°C and 300°C and 20-40 % at 150°C . Independent of other air parameters the weight losses increased by about 30 % on going from 3 m/s to 9 m/s.

The prefried product which was reheated at low temperatures showed only minor weight losses during the reheating procedure. One has to consider, however, that the preparation procedures, i.e. like frying, gave higher weight losses than boiling. Increasing the temperature from 125°C to 150°C did not affect the extent of the losses. However, they were

relatively high at further increase of temperature up to 200°C . This is notable when reheating in humid air. In humid air this procedure gave almost zero losses at 125°C and 150°C . Furthermore it was evident that, taking the total procedure into consideration including preparation ("boiling" or "frying"), storage and reheating, the prefried product in general lost less weight than the boiled one at the same air parameters. Although the "boiled" product was formed without any losses, the results indicate that the changes in the product, during boiling, facilitates the loss of water while the crust is formed. For example a product which was boiled at 125°C , 5 m/s and humid air and then stored and reheated at 150°C , 9 m/s and "dry" air gave total losses of about 17 %. On the other hand, when the product was fried at 150°C , 9 m/s and dry air , then stored and reheated at 125°C , 5 m/s and humid air these losses were about 8.5 %.

A satisfactory crust colour was obtained after reheating only at the lowest temperatures irrespectable of other air parameters and preparation procedure (11). Comparing the colour after reheating with a fresh fried product processed at the same air parameters and recipe, the reheated ones gave darker colour in general (8). Boiling of minced meat seems to facilitate the browning reaction.

The thiamine losses were in general moderate and only in the case of severe heat parameters, causing overheating of the outer parts of the loaf, there were losses around 30 percent.

The weight losses and the crust colour were remarkably influenced when reheating was performed above a certain temp-

erature. These observations strengthen the conclusions that when the surface of the product had reached 100°C the temperature in the centre was not dependent on the air parameters. Additional energy supplied was used to evaporate water, heat the crust and help the 100°C isotherm to move towards the centre. At low temperatures, low velocities and dry air the time until the surface reached 100°C was relatively long and was influenced by changing air parameters.

The conclusions made from this investigation were

- 1) To get a crust colour that is not too dark, air temperatures below 200°C should be used.
- 2) It is possible to form a crust on a "preboiled" meat loaf. To get a satisfactory colour the temperature should be below 200°C .
- 3) Reheating of a "boiled" minced meat loaf gives darker products than frying at the same air parameters. Boiling facilitates browning reactions.
- 4) The weight losses are very low when reheating a prefried product.
- 5) Below a certain air temperature heating time could be influenced by increasing velocity or humidity of the air.

Thus to get minimum weight losses and a satisfactory colour, reheating should be performed under 200°C . The product should be "prefried" and should possess a satisfactory crust colour.

The reheating time could be speeded up by using high air

velocity or high air humidity. These conclusions are further strengthened by the results from the sensorial analysis where the prefried product was better than the "boiled". In addition, the sensory properties of the prefried product were similar to the reference sample.

Acknowledgements.

This project was supported by the National Swedish Board of Technical Development. Many thanks to Anders Ånäs and Per Sjödin who carried out most of the experimental work.

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Figure legends.

Figure 1. Research convection oven.

Figure 2. Reheating time of "fried" product as a function of air velocity. Temperature and humidity of air are parameters.

Figure 3. Reheating time of "boiled" product as a function of air velocity. Temperature and humidity of air are parameters.

Figure 4. Weight losses not including preparation and storage during reheating of "fried" product as a function of air velocity. Temperature and humidity are parameters.

Figure 5. Weight losses (not including preparation and storage) of the "boiled" meat loaf as a function of air velocity. Temperature and humidity of air are parameters.

Figure 6. Colour of the "fried" meat loaf as a function of air velocity. Temperature and humidity of air are parameters.

Figure 7. Colour of the "boiled" product after reheating as a function of air velocity. Temperature and humidity are parameters.

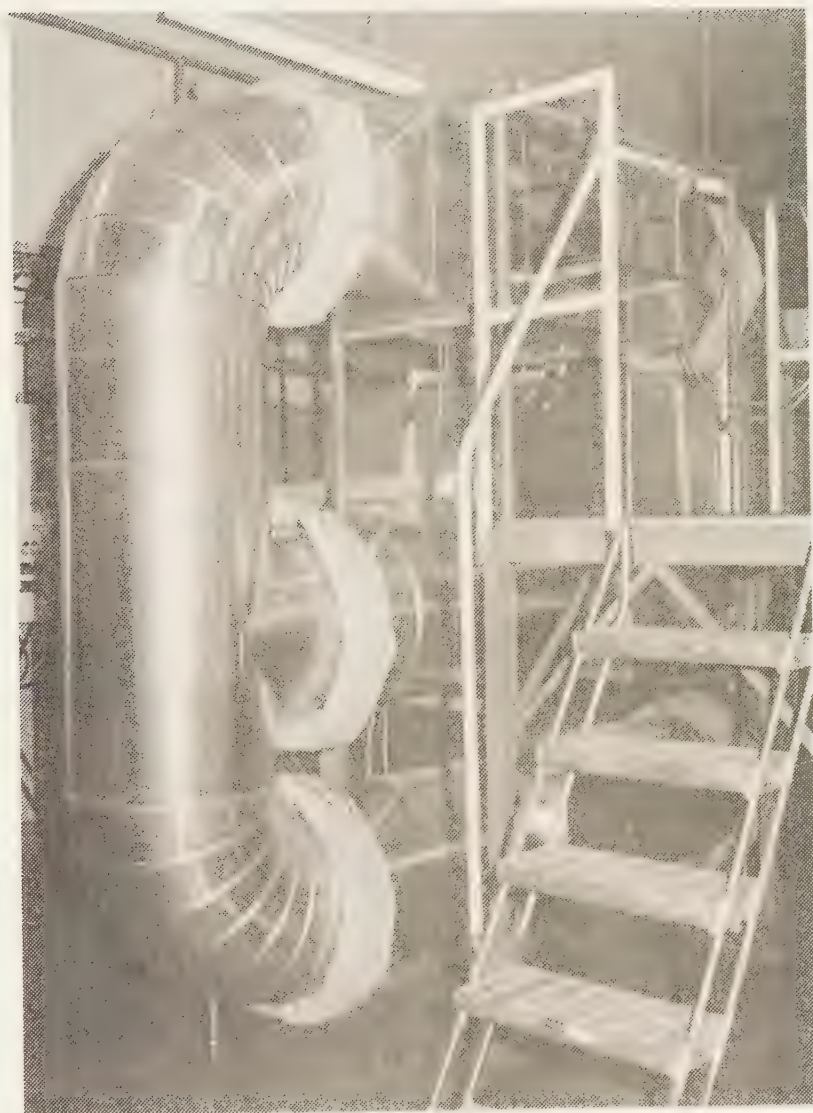
Figure 8. Thiamine retention after reheating of the "fried" product as a function of air velocity. Temperature and humidity are parameters.

Figure 9. Thiamine retention after reheating of the "boiled" product as a function of air velocity. Temperature and humidity are parameters.

Figure 10 Sensorial property, odour, as a function of air velocity.

Figure 11. Taste after reheating as a function of air velocity.

Figure 12. Appearance after reheating as a function of air
velocity.



Time (min)



60

50

40

30

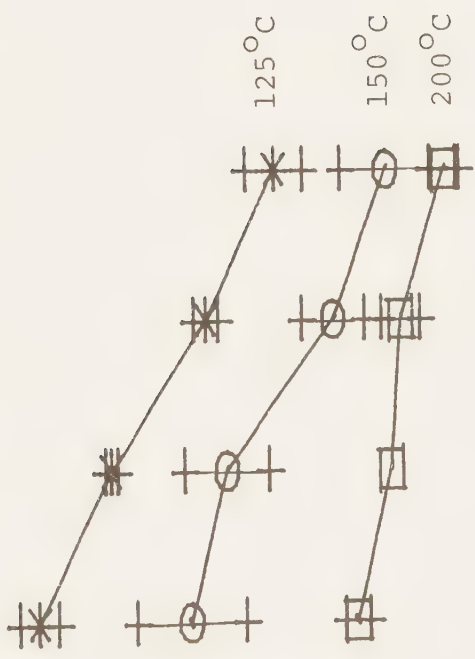
20

10

0

Dry air

Humid air



125°C

150°C

200°C



Air velocity (m/s)



9

7

5

3

9

7

5

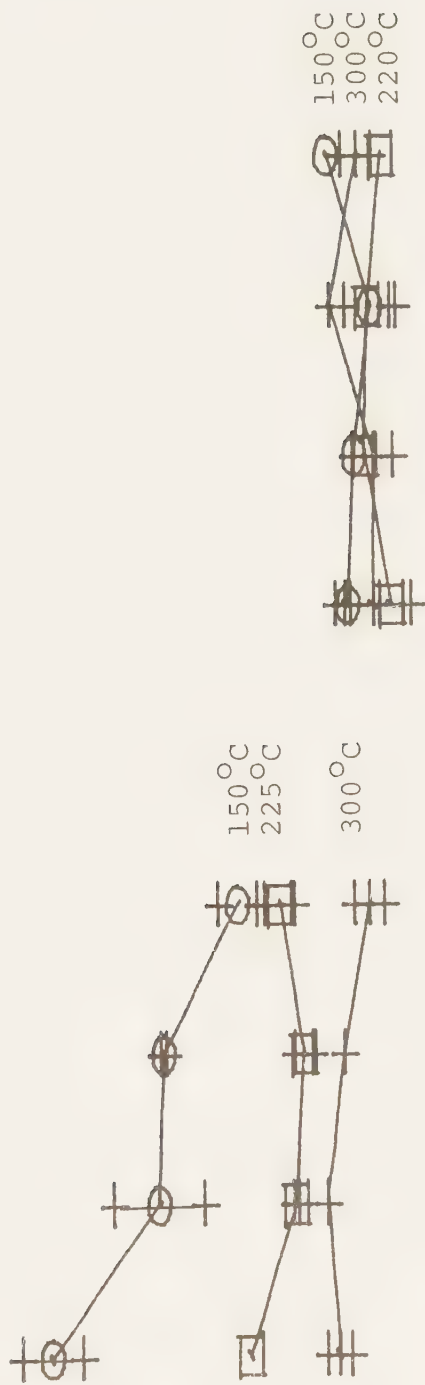
3

Time (min)



Dry air

Humid air



9 Air velocity (m/s)

7

5

3

9

5

5

3

Weight losses (%)

30
20
10

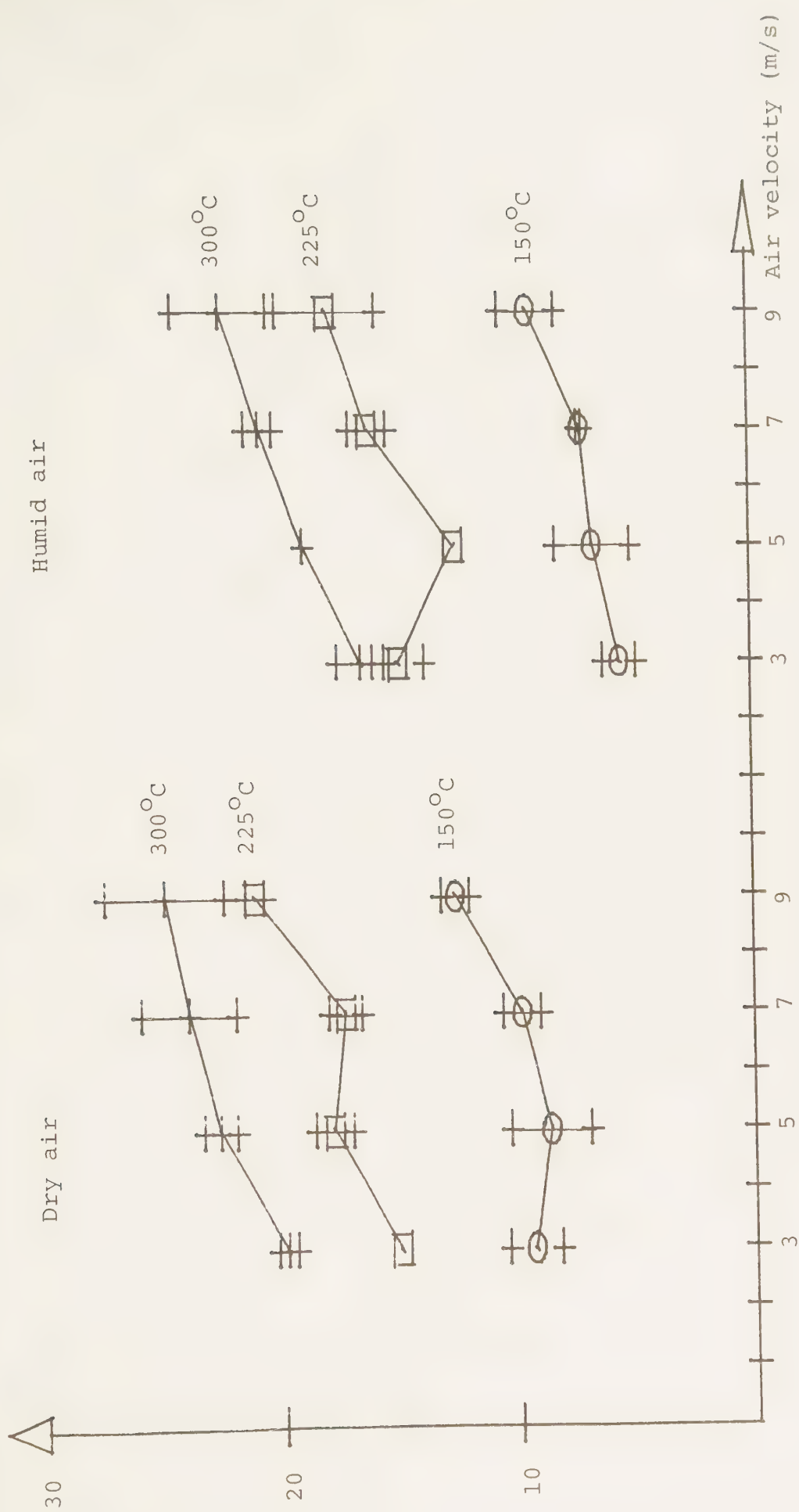
30
20
10

Dry air

Humid air



Weight losses (%)

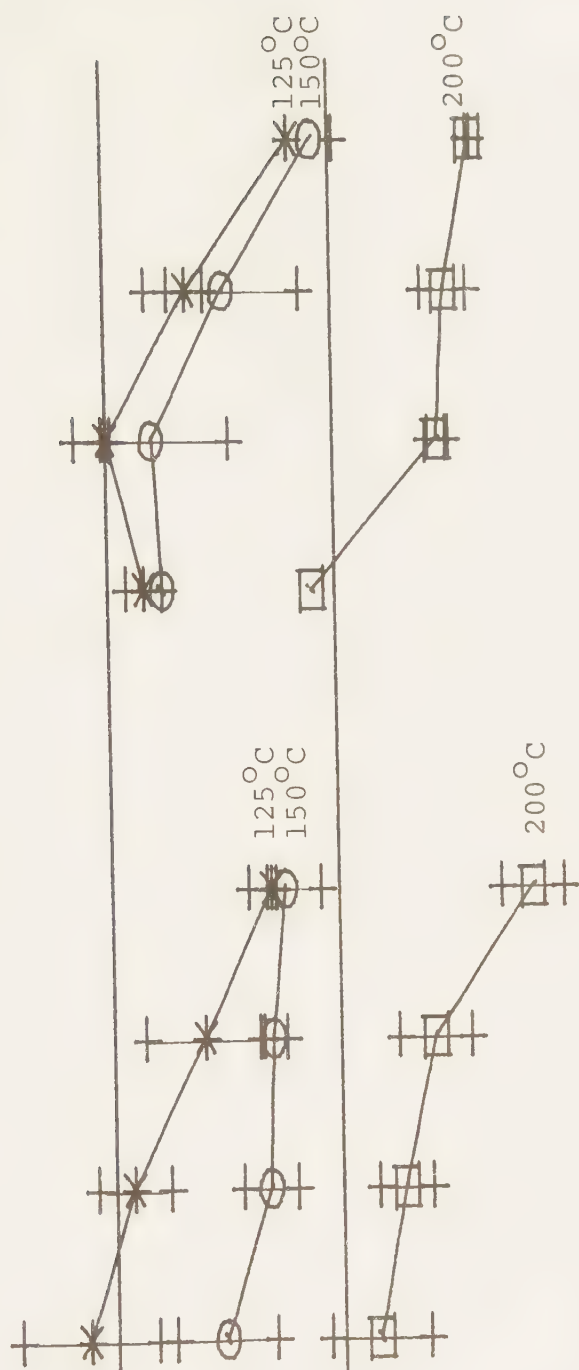


Brightness (%)

20
10
0

Dry air

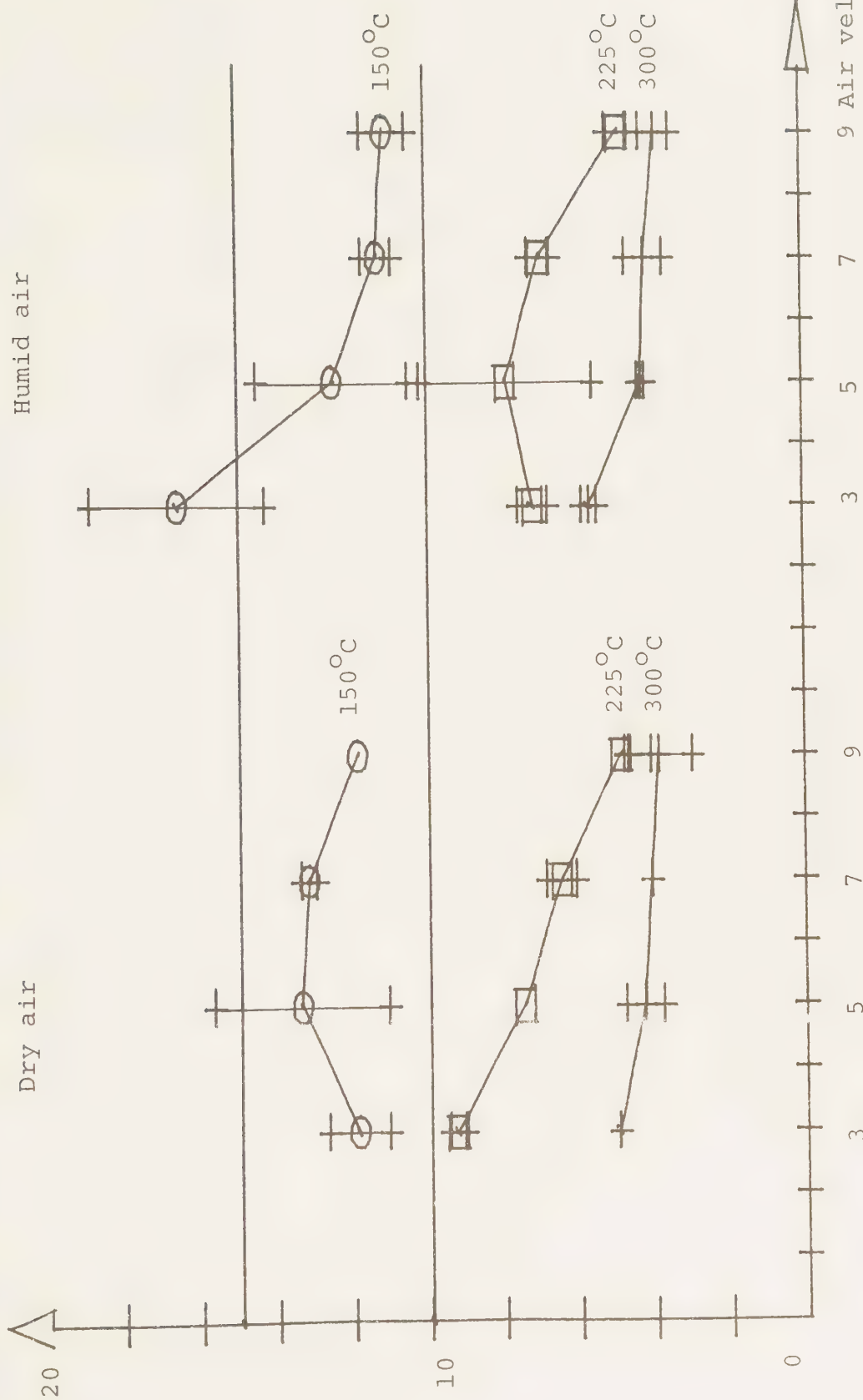
Humid air



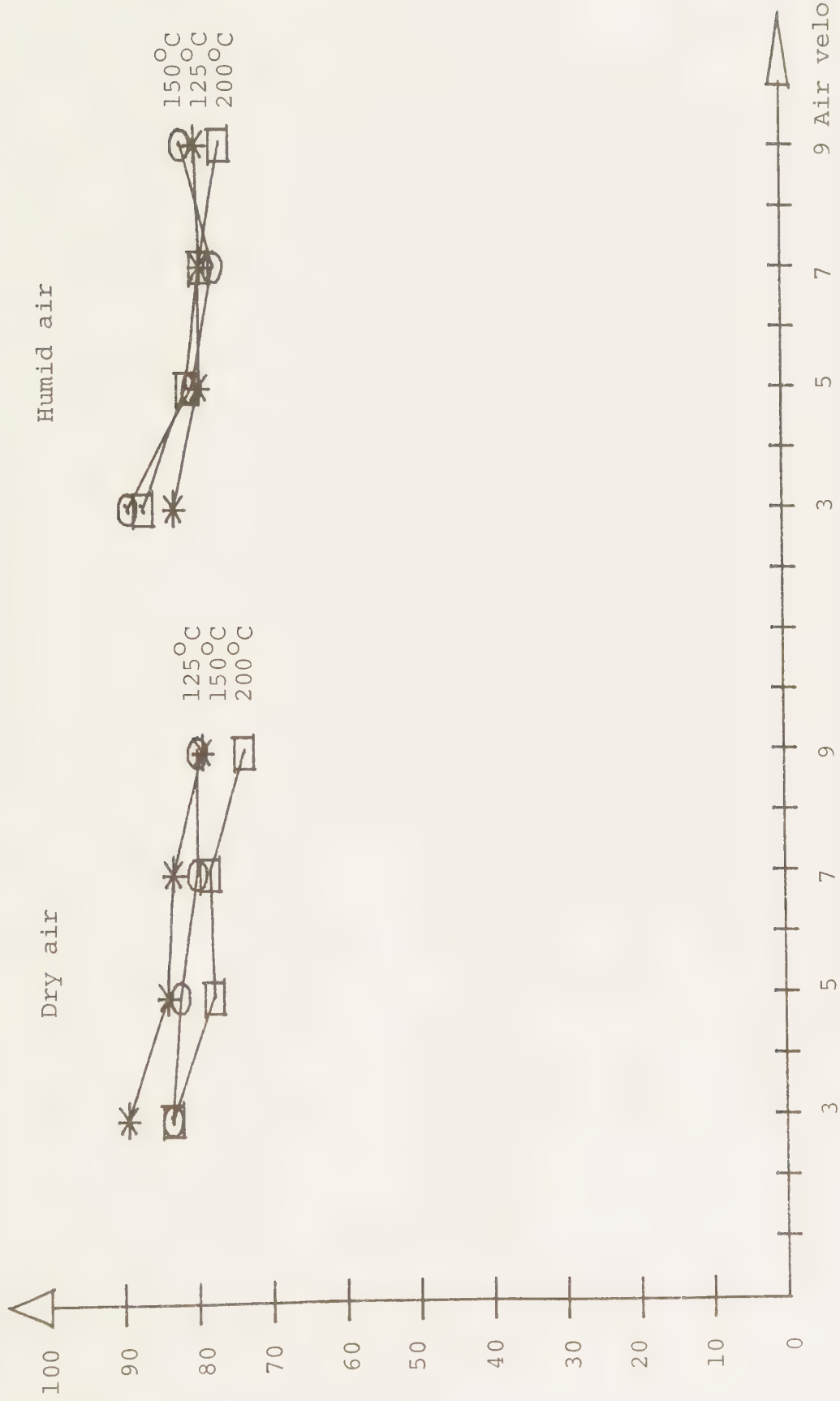
Air velocity (m/s)



Brightness (%)



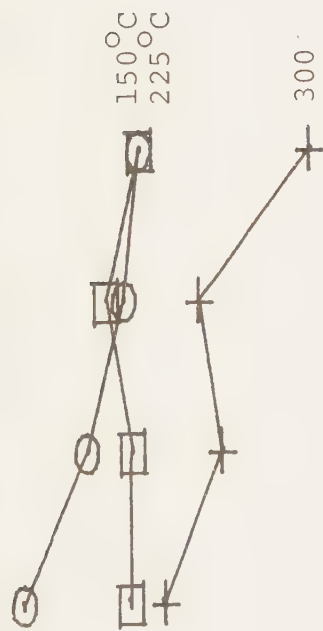
Thiamine retention (%)



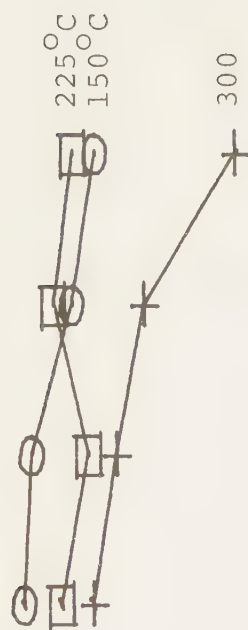
Thiamine retention (%)

100
90
80
70
60
50
40
30
20
10
0

Dry air

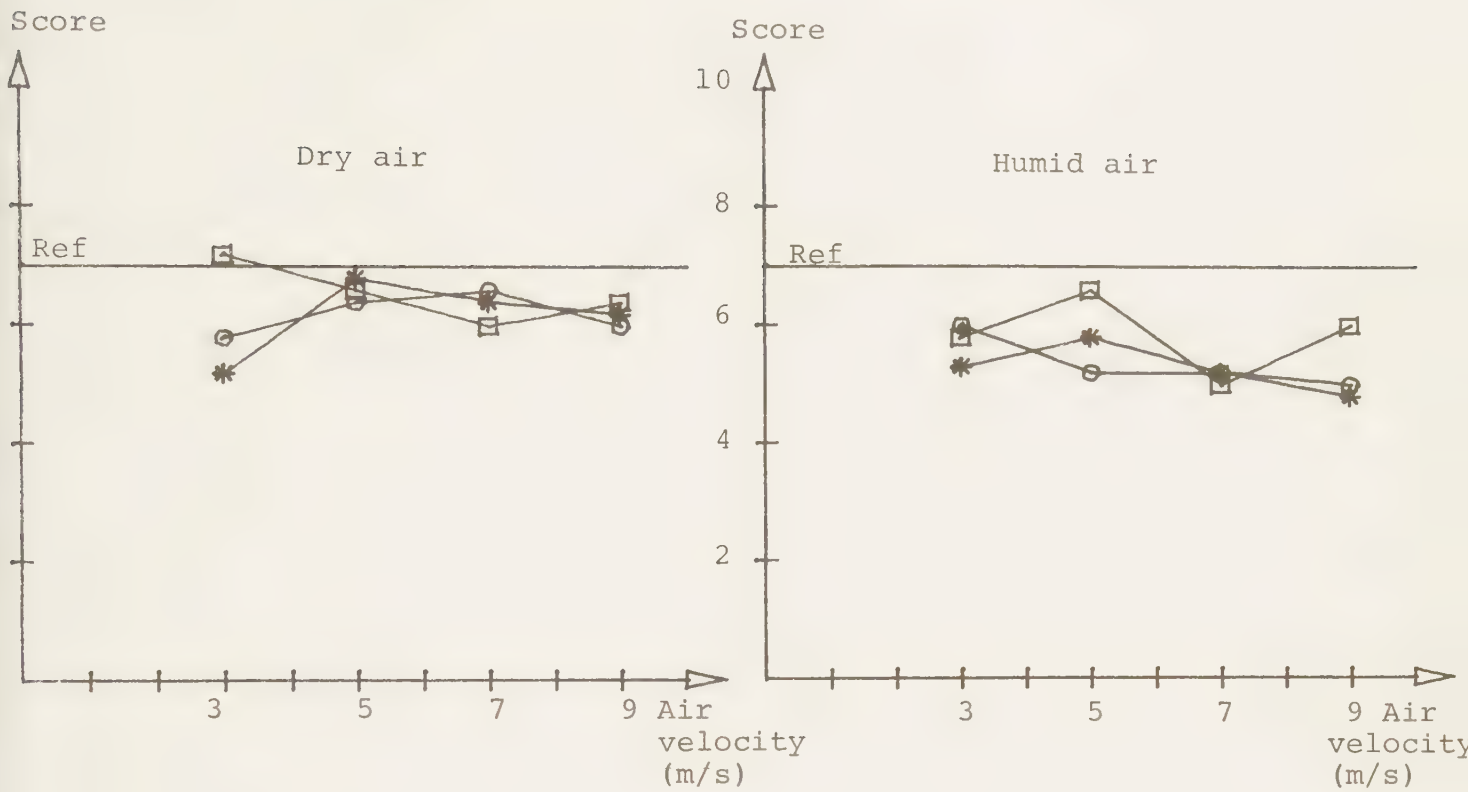


Humid air

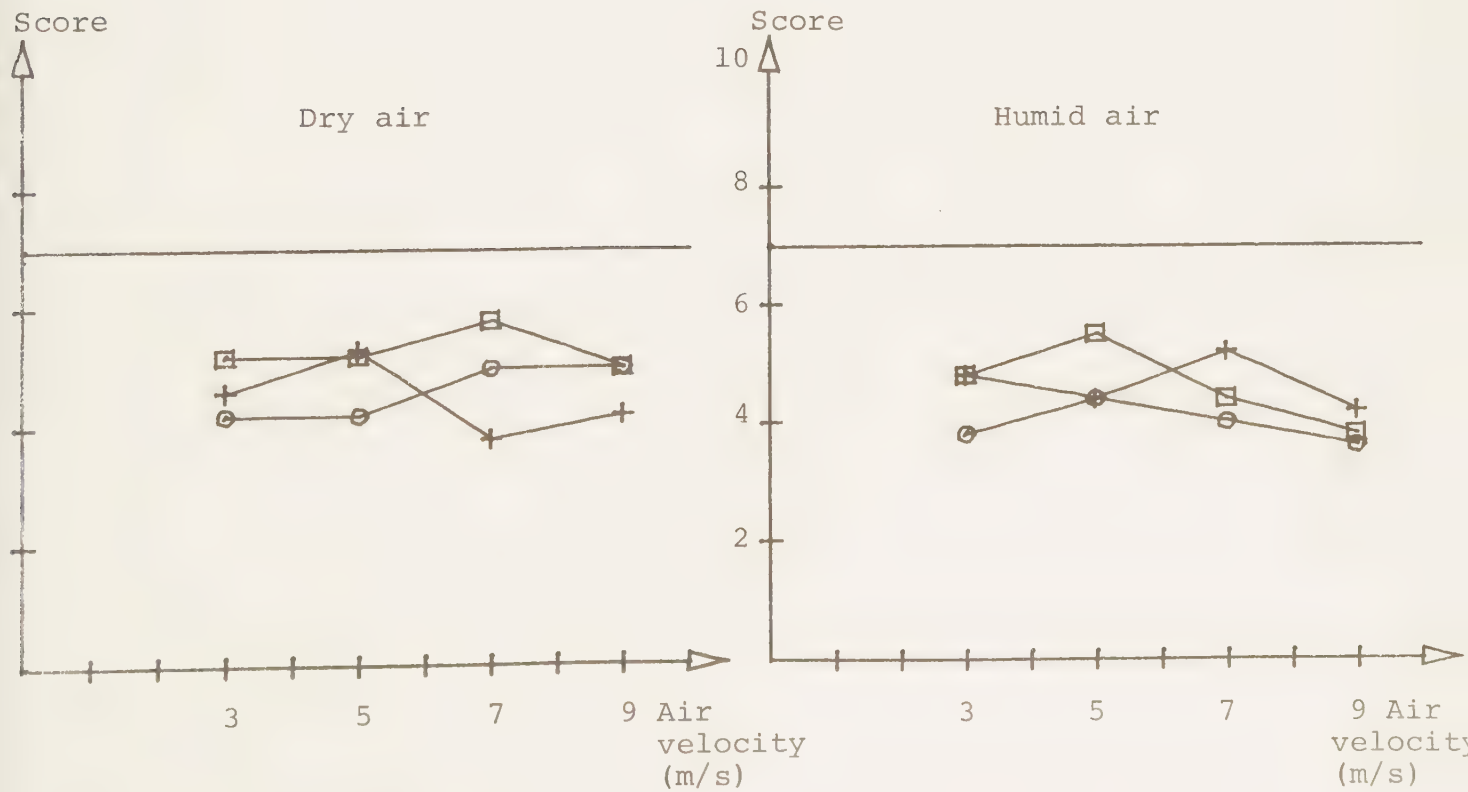


9 Air velocity (m/s)

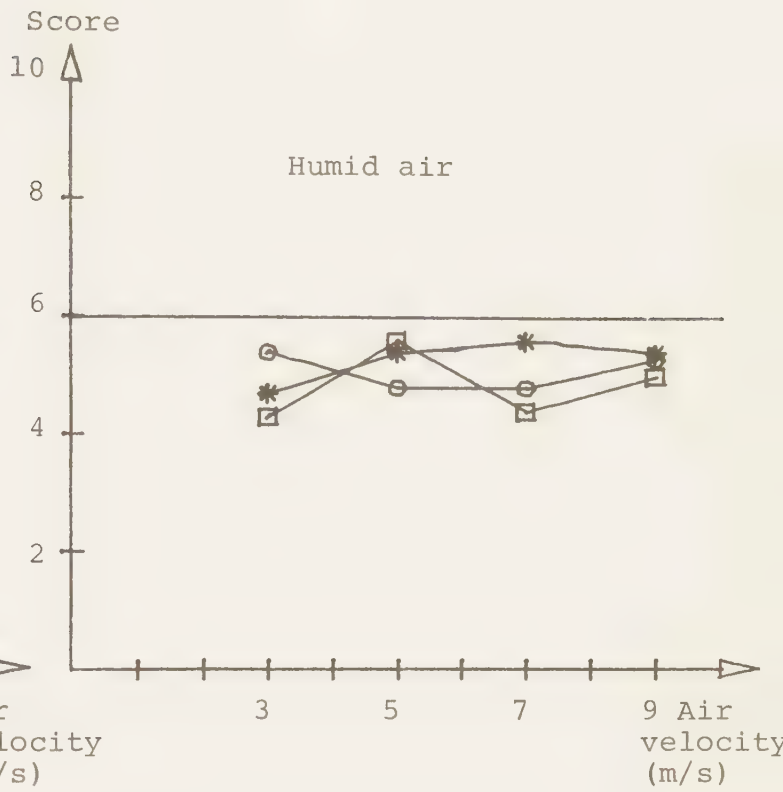
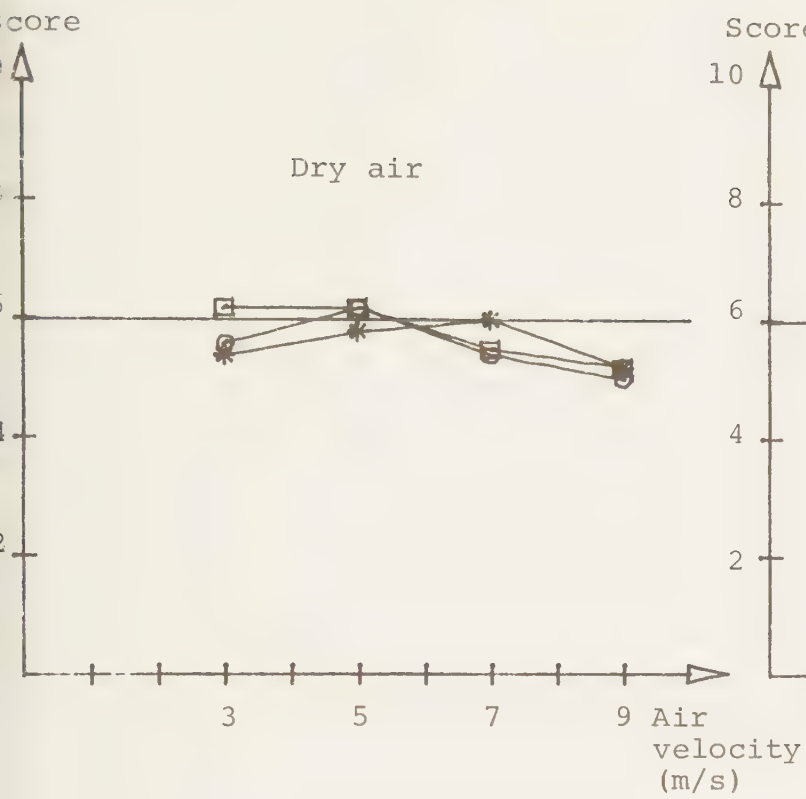
"Fried" product



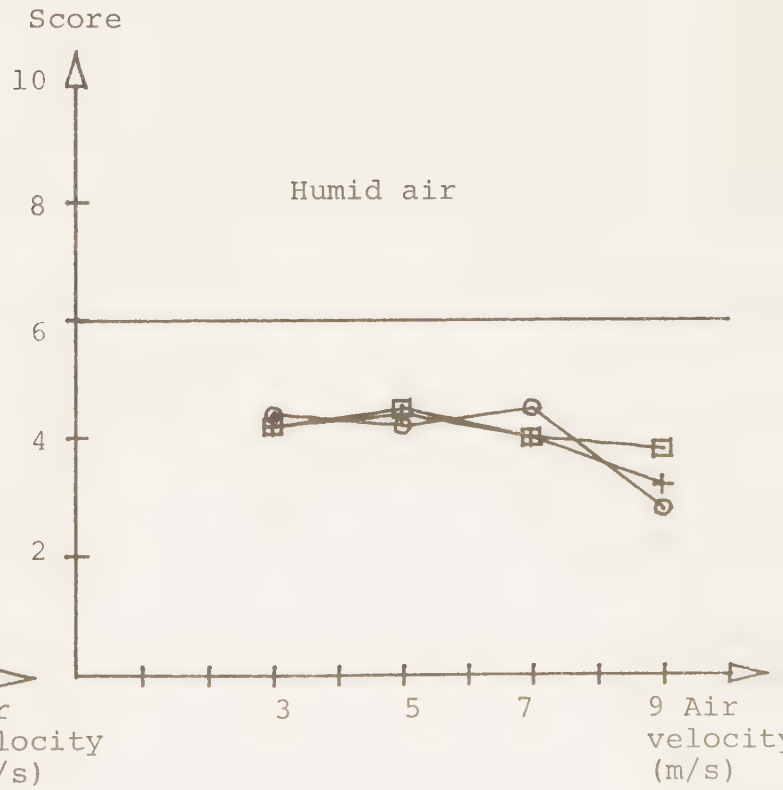
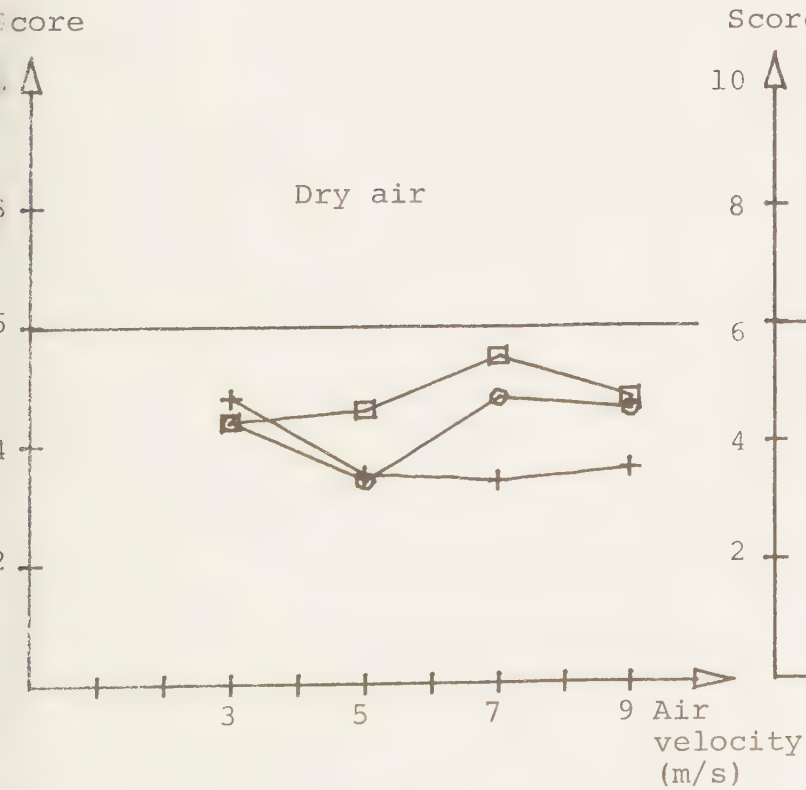
"Boiled" product



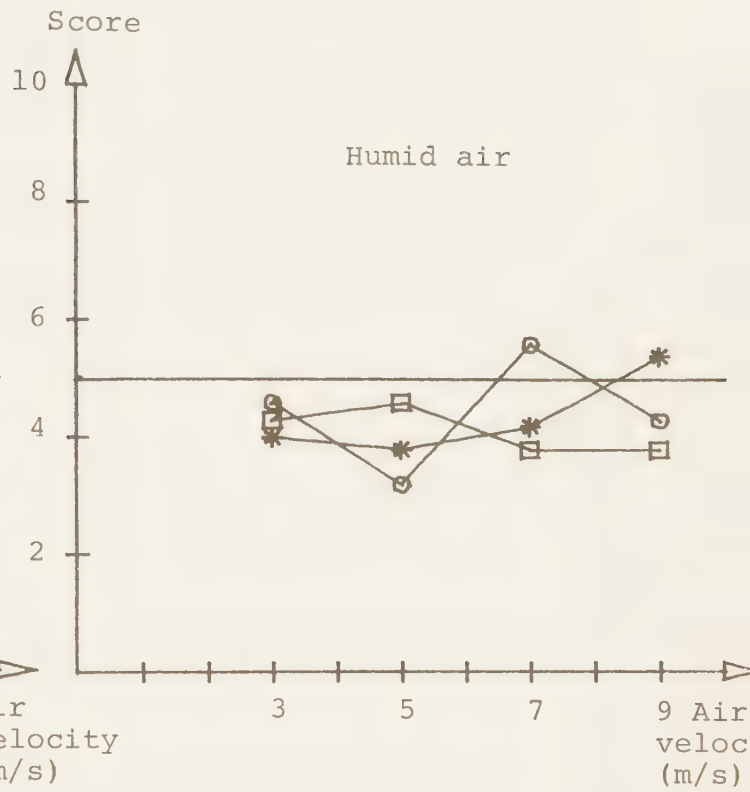
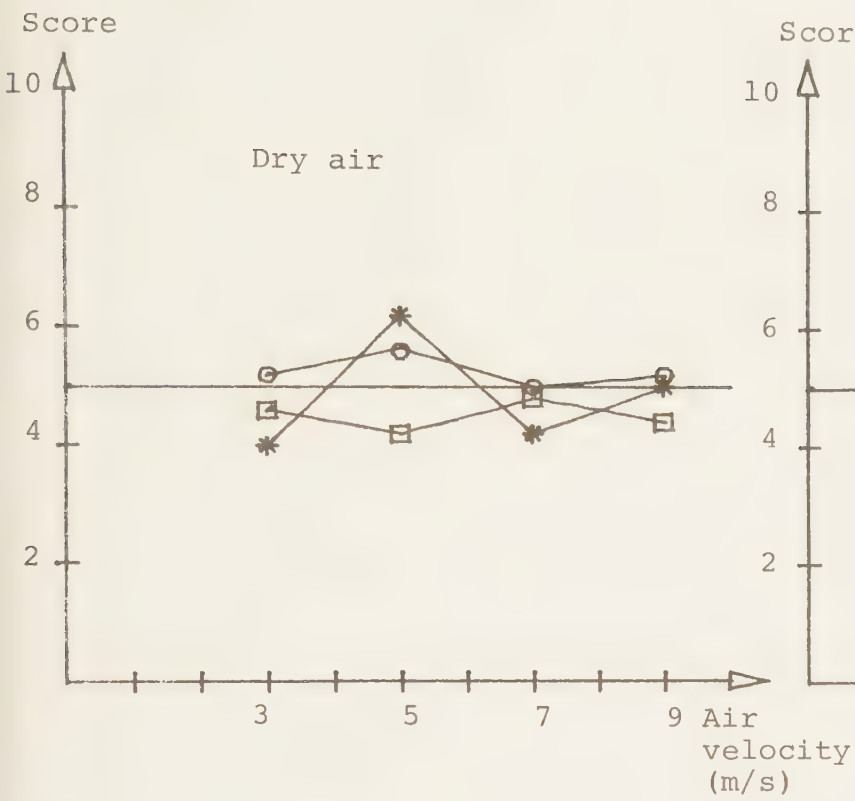
"Fried" product



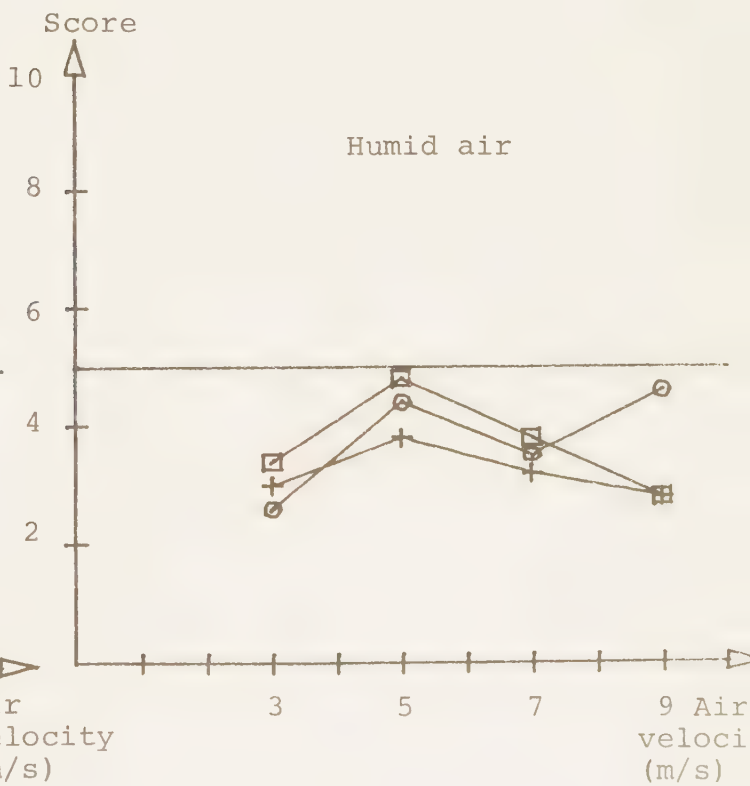
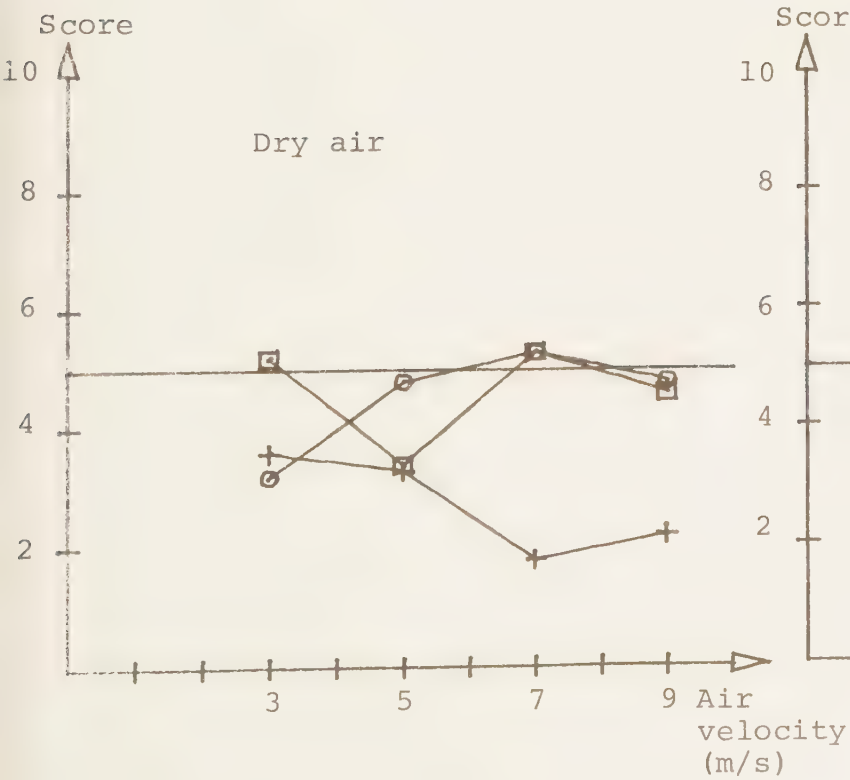
"Boiled" product



"Fried" product



"Boiled" product



Abstract.

CONVECTION OVEN FRYING I. HEAT AND MASS TRANSFER BETWEEN
AIR AND PRODUCT.

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Heat and mass transfer between air and product, fried in a specially designed forced convection oven, were analysed. Minced meat loaves of an industrial recipe were fried for one hour at different temperatures, humidities and velocities of the air. It was shown that the moisture loss rate was larger in the beginning of the frying than at the end. The heat transfer coefficients varied between 20 and 90 W/m² °C. These values are low compared with other frying methods. The mass transfer coefficients varied between 0.04 and 0.115 m/s. The coefficients decreased remarkably going from the constant rate period to the falling rate period.

Convection oven frying I. Heat and Mass Transfer between air and product.

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Introduction.

One of the most useful machines in catering establishments is the forced convection oven and in this the product is exposed to circulating hot air. This means that air transfers heat to the product from which, at the same time, water is transferred to the air.

In frying the heat supplied to the product causes protein denaturation and destroys harmful organisms. Decreased moisture content in combination with sufficient high temperature in the surface layer causes chemical and structural changes that form a crust.

To be able to optimize the frying operation the mechanisms for heat and mass transfer have to be investigated. Frying in the convection oven is a drying operation at high air temperatures. The distinction from, for example, drying of vegetables is that only the surface should be dried. This means that theories for drying can be used.

Several textbooks present theories for the drying mechanisms in solid matters. Krischer, (1963), Keey (1972), Kneule (1975), Lykow (1955) have discussed the basic principles. Godsalve et al., (1977) and Hung et al., (1978) examined the heat and mass transfer when cooking meat muscles in dry air. Dagerskog (1978) studied the fundamental process calculation for contact frying of food products.

In this study the heat and mass transfer between air and product, fried in a specially designed forced convection oven, were analysed. Meat loaves of defined size and recipe were used. Sörenfors (1978) studied temperature measuring techniques and physical phenomena of deep fat frying. Some of his results and conclusions were used in this investigation.

Theory

A material that is convection air dried/fried derives heat from an air stream moving over the material. The cold body gains heat that is proportional to the temperature difference between the surrounding air and the surface of the body. The coefficient of proportionality is defined as the heat transfer coefficient α . This is analogous to the mass transfer of water to air which is proportional to the difference between partial vapour pressure at the surface and in the air; this coefficient is called the mass transfer coefficient β . The heat flux to and the water flux from the product could be changed by varying the temperature, humidity and velocity of the air. The geometry of the product is also of importance.

It is sometimes convenient to evaluate α and β in terms of their dimensionless numbers. For heat transfer there is a Nusselt number

$$Nu = \frac{\alpha \cdot \ell}{\lambda}$$

where ℓ is a characteristic length and λ is the thermal conductivity of the air.

Analogous for mass transfer there is a Sherwood number Sh

$$Sh = \frac{\beta \cdot \ell}{D}$$

where D is the diffusion coefficient of water in the air
The following correlations are given

$$Nu = C_1 \cdot Re^m \cdot Pr^n$$

$$Sh = C_2 \cdot Re^k \cdot Sc^o$$

where C_1 and C_2 are constants.

The exponent m, n, k and o vary between 0 and 1

$$Re = \frac{v \cdot \ell}{\nu} \quad ; \quad Pr = \frac{\nu}{a} \quad Sc = \frac{\nu}{D}$$

where v is the velocity, ν is the kinematic viscosity and α the thermal diffusivity. For air the Prandtl number (Pr) is almost constant (~ 0.7). The exponents and the constant could be determined by experiments at defined air temperature, air humidity and air velocity.

With regard to transfer conditions between air and product three stages can be separated. Initial temperature of the product is t_o .

1. During the first stage the surface temperature is raised to the dew point $t_d = t_w$. As long as t_s is lower than t_d condensation takes place e.g. there is a transfer of moisture from the air to the product. However, the amount of water transferred is very small. This stage is signified by a relatively high transfer coefficient.
2. When t_s has reached t_w , the constant rate period of drying starts which is characterized by a constant rate loss of moisture and this is independent of the moisture that is present in the solid. Moisture is transported from the interior to the surface faster or at the same rate as the water is evaporated into the air. At this moment there is a change in transfer coefficient. In these types of operations this stage is found to be very short and sometimes cannot be observed on the temperature curves which will be shown later.

3. After this follows the falling rate period and the surface temperature starts to raise above t_w . At the moment when this period starts there is not sufficient water on the surface to evaporate at the same rate. The evaporating zone is displaced into the product from the product surface. During this period the transfer coefficients falls below earlier figures. In this investigation the mass transfer surface has been equalized to the heat transfer surface.

Material and Methods.

Aparatus

A specially designed oven for investigation purposes was used (Skjöldebrand 1976). This is built like a wind tunnel (figure 1) in which it is possible to reverse the air stream. The air is dispersed with aid of guide plates and finely meshed netting over the oven cavity. This has the dimensions 325 x 325 x 325 mm and is provided with three shelves, where the product can be placed. A plane of glass is placed on the upper roof. Temperature, humidity and velocity of the air can be carefully controlled. Steam is added in front of the fan which in turn is placed in front of the heating elements. A maximum power effect of 15 kW can be supplied. A Prandtl tube measures the velocity (2-12 m/s) and a specially designed unit the humidity (between completely dry air and pure steam), (Sörenfors et al., 1977). Air Temperature is measured by a chromel-alumel thermocouple and can be regulated between 20-400°C. Temperature in the product is measured according to recommendations made in an investigation carried out at the institute (Sörenfors 1978). Chromel-

alumel thermocouples with a total diameter of 0.5 mm are used (thread diameters 0.12 mm). An IR sensing head measures the surface temperature. (Raytek Thermalert LC-814). The infrared-radiation is a function of the surface temperature. This sensing head is called a partial radiating pyrometer. This means that it only takes radiation of a special wave length and measures through for example the water molecules in the air. The wavelengths used are between 8 and 14 microns. The moisture loss rate can be measured continuously on a balance placed in the oven cavity. The product is hung on a wire coupled to strain gages (Hottinger Baldwin) held on a frame placed outside the plane of the glass. All temperature, humidity, velocity and weighing values pass a data-logger and are registered on a punched tape for later computer evaluation.

Experimental Procedure

Minced meat of an industrial recipe was made into a loaf 200 x 50 x 50 mm. The composition of the minced meat was ash 12.6 %, fat 13.7%, protein 10.7% and water 63%.

The loaf was placed in a teflon-coated cage to avoid change of shape during frying. The cage was hung on the balance during the frying procedure. The product was placed with its short side towards the air stream. The weight loss was recorded continuously. The IR sensing head measured the surface temperature. Chromel-alumel thermocouples were sewed into the product some millimeters under the surface and in the center from the short side of the product. In this way the temperature gradient

over the thermocouple was minimized according to the recommendations of Sörenfors, 1978. The positions were checked after frying. The frying was conducted for one hour according to table 1. The air stream was reversed the first minute every 15 th second and every minute for the rest of the time.

Special Measurement Problems

There were many difficulties in measuring temperatures with thermocouples placed in a product. In this investigation the following steps were to avoid measurement errors according to recommendations of Sörenfors (1978). These are a) chromel-alumel thermocouples instead of Copper-Constantan were use because of the lower thermal conductivity of the thread, b) the temperature gradient over the thermocouple was minimized, c) a thermocouple thread with minimum thickness was chosen as the error is proportional to its diameter.

When measuring the surface temperature the IR sensing head was used. The temperature is proportional to the IR radiation from the surface and this proportionality depends on the reflecting properties of the product. This IR-sensing head was prepared for measuring black bodies or almost black bodies. This means that at the beginning of the frying the error in surface temperature due to the brightness could be $\pm 5^{\circ}\text{C}$ but was reduced as the crust was formed.

There were difficulties in measuring the weight losses, as the movement of the air stream disturbed the balance. From the weight values an integrated curve was designed thus giving useful

values for the moisture loss rate. There was uncertainty about the moisture loss rate figures in the investigation. A small change in these figures, however, would not change the transfer coefficients very much.

Calculations.

A mean value of the different properties over three different stages of the frying was determined.

1. The period equivalent to the constant rate period.
2. The falling rate period that was divided into two parts.
 - a) The first one part was from the end of the constant rate period until the center of the product had reached 70°C. A temperature of 65-70°C in the center is considered a ready-made product.
 - b) The second part was from the time the center was 70°C until 45 minutes frying time.

Furthermore, a total mean value for the total frying time was calculated.

From the weight loss curve the moisture rate loss was determined.

According to basic drying theories α was estimated by the following relationship (Lykow 1955)

$$\begin{aligned}
 Q &= A \cdot \alpha (t_a - t_s) = c_{po} \rho_o \cdot V \cdot \frac{dt_m}{d\tau} + r \cdot \frac{dG}{d\tau} = \\
 &= (c_{pt} + x \cdot c_{pw}) \cdot G_t \cdot \frac{dt_m}{d\tau} + r \cdot \frac{dG}{d\tau}
 \end{aligned}$$

The partial vapour pressure at the surface, p_{Ds} was calculated from the Lewis relationship (Krischer 1963; Kneule 1975; Sörenfors et al., 1977; Bruin et al., 1977)

$$\frac{\alpha}{\beta} = c_p \cdot \rho \cdot Le^{2/3} \left(1 - \frac{p_{Dm}}{p}\right)$$

$$\rho \cdot c_p = \rho_L \cdot c_{pL} + \rho_D \cdot c_{pD} = \frac{p - p_D}{R_L \cdot T} \cdot c_{pL} + \frac{p_D}{R_D \cdot T} c_{pD}$$

$$Le^{2/3} \approx 1$$

$$p_{Dm} = \frac{p_{Ds} + p_D}{2}$$

The mass transfer coefficient, β was calculated from

$$\frac{dG}{d\tau} = \frac{\beta \cdot A}{R_D \cdot T} (p_{Ds} - p_D)$$

Data for c_{pt} , c_{pL} , c_{pD} , c_{pw} and p_D were taken from literature (Sörenfors 1978; Sörenfors et al., 1977; Bruin et al., 1977). Table 1 shows partial vapour pressure of air bulk and saturated vapour pressure on surface at different air humidities.

The surface water content was determined in the following way. The vapour partial pressure of the product is related to moisture content according to its sorption isotherm assuming at each moment that equilibrium is reached (Skjöldebrand et al.). The sorption properties of the product are influenced not only by

the actual temperature but also by the degree of heat denaturation, i.e. the time-temperature history of the product. When these relations as well as the surface temperature as a function of time are known, the surface water content can be calculated according to Skjöldebrand et al.

From the calculated heat and mass transfer coefficients the exponent for Reynolds number in the dimensionless correlations were calculated at each combination of air parameters. α and β were plotted against air velocity in a log-log diagram at constant air temperature and humidity. The Prandtl number and the Schmidt number were assumed to be constant.

Results.

1. Moisture loss rate

Figure 2 shows the moisture content of the meat loaf as a function of frying time at 150°C and 225°C. The moisture loss rate was calculated from these curves and is presented in table 2. At the start the moisture loss rate was large but decreased at the end.

2. Heat transfer coefficient.

Figure 3 and 4 shows the surface temperature of the loaves as a function of time at 150°C and 225°C. When the center of the product had reached 70°C the surface temperature varied between 95°C and 160°C and after 45 minutes between 100°C and 173°C.

Knowing the moisture loss rate and the surface temperature curves, the heat transfer coefficients were calculated for the different periods and the results are shown in figure 5. These values varied between 20 and 90 W/m² °C.

3. Mass Transfer coefficient.

Figure 6 shows the mass transfer coefficients as function of time. These values varied between 0.04 and 0.115 m/s.

4. Surface moisture content.

In the constant rate period, the water activity on the surface was 1 and the partial vapour pressure equalized the saturated water pressure at actual surface temperature. At 150°C, 5 m/s and humid air the surface temperature did not exceed 100°C during the actual frying period.

Table 3 shows the calculated water contents of the surface layer for the different frying experiments.

5. The exponents on Reynolds number in the dimensionless relationships.

Figure 7 shows the heat transfer coefficient as a function of air velocity at different air temperatures with "dry" air. The slope of each line gave the value of the exponent on the Reynolds number, which for all parameters was 0.45 ± 0.05 .

The exponent on the Reynolds number in the dimensionless relationship for mass transfer was found to be 0.46 ± 0.08 .

Discussion.

Figure 2 shows that an increase in velocity or temperature resulted in a larger total weight loss after the same frying time. An increase, however, of air humidity meant a lower loss. The moisture content at the end of drying is controlled by the relative humidity of the air and the sorption isotherm of the product at actual air temperature. It was shown that the moisture loss rate was larger in the beginning than at the end. From table 2 it can be seen that the rates decreased dramatically from the constant rate period to the falling rate.

The surface temperatures showed that an increase in air humidity gave a longer constant rate period but an increase in air temperature shortened it. This can be explained from the mass transfer equation. Theoretically during the constant rate period a constant amount of water should disappear from the product. This gives the following relation if the mass transfer coefficient is assumed to be constant

$$\Delta G = \frac{A \cdot \beta}{R_D \cdot T} \Delta p \cdot \Delta \tau \approx \text{const} \cdot \Delta p \cdot \Delta \tau$$

$$\Delta \tau \approx \frac{G}{\Delta p} \cdot \text{const} \quad \Delta p = (p_{Ds} - p_D)$$

Discrepancies from this could be caused by the following

- 1) More water condenses on the surface at humid air than at "dry" before reaching the wet bulb temperature.
- 2) Changes in physical properties of the surface due to chemical changes deriving from temperature and moisture development.

This should be an object for further research. The heat transfer coefficient increased as the moisture loss rate become larger and the surface temperature raised faster when the air velocity increased. From figure 5 and 6 it can be seen that both the heat transfer and the mass transfer coefficients decreased remarkably going from the constant rate period to the falling rate period. It seems, however, that during the constant rate period an increase in air temperature does not effect the heat transfer coefficient. The variation of the coefficient was larger within one frying experiment than between different air temperatures 150°C and 225°C. The heat transfer coefficient is about the same at 225°C as at 150°C at the same surface temperature which means that the energy transport is larger at the higher air temperature.

The result shows that the heat transfer coefficients are fairly low compared with other frying methods (Dagerskog 1978, Sörenfors 1978). This can have an effect on the kind and size of products which are suitable for frying in a convection oven. The low heat transfer coefficient means a high resistance against transport.

The mass transfer coefficient increases with temperature, velocity and humidity.

The calculated exponents of the Reynolds number in the dimensionless correlations of heat and mass transport are in good agreement with the values found in literature (Keey 1972; Housova 1973).

When the surface temperature had reached 100°C the water content decreased very rapidly towards the equilibrium moisture content according to the sorption isotherm at surface temperature. In the actual investigation the surface temperature reached its highest of 170°C with a surface water content of 1%. The water content was calculated from a model for the sorption isotherm (Skjöldebrand et al., 1979) based on a modified Helsey equation (Cherife et al., 1976). This model is most suitable for water activities between 0.1 and 0.8 but the surface water activities were very low in our investigation most of them being below 0.1.

When the constant rate period ended the surface temperature started to rise, rapidly in the beginning of the falling rate period but slower at the end approaching the oven temperature. When the surface temperature had reached 100°C a crust was formed and the surface water content decreased rapidly.

The results from this investigation give the magnitude of the heat and mass transport between the air and the product for

convection oven frying of meat loaves. The conclusions are that:

1. To get as low moisture loss as possible frying/drying should be performed at a low air temperature and at high air humidity.
2. To get a center temperature of 70°C as fast as possible and at the same time a minimum weight loss, the air temperature should be low in combination with high air humidity and low air velocity. This can be explained from the heat transfer coefficients of the constant rate period and the length of this period.
3. To get a proper crust the air should be dry at least at the end of the frying.

Information on the heat and mass transfer coefficient give some basic data needed to make a model for the optimization of frying in a convection oven. This investigation gives the variation of these coefficients as a function of frying periods and air parameters.

Acknowledgements.

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Nomenclature

A	heat and mass transfer area (m^2)
a	thermal diffusivity (m^2/s)
C_1, C_2	constants
c_{po}	specific heat of product ($Ws/kg\ ^\circ C$)
c_{pt}	specific heat of dry product ($Ws/kg\ ^\circ C$)
c_{pw}	specific heat of water in product ($Ws/kg\ ^\circ C$)
c_p	specific heat of humid air ($Ws/kg\ ^\circ C$)
c_{pL}	specific heat of dry air ($Ws/kg\ ^\circ C$)
c_{pD}	specific heat of vapour in air ($Ws/kg\ ^\circ C$)
D	diffusion coefficient (m^2/s)
G	weight of product (kg)
G_t	weight of dry product (kg)
l	length (m)
k, m, n, o	constants
p	pressure of air (N/m^2)
p_{Dm}	mean partial vapour pressure (N/m^2)
p_D	partial vapour pressure of air (N/m^2)
p_{Ds}	partial vapour pressure of surface (N/m^2)
Q	energy (W)

R_L	gas constant of air ($Ws/^{\circ}K$; kmol)
R_D	gas constant of water vapour ($Ws/^{\circ}K$; kmol)
r	heat of evaporation (Ws/kg)
T	absolute temperature ($^{\circ}K$)
t_o	initial temperature ($^{\circ}C$)
t_w	wet bulb temperature ($^{\circ}C$)
t_s	surface temperature ($^{\circ}C$)
t_a	air temperature ($^{\circ}C$)
t_n	mean temperature of product ($^{\circ}C$)
V	volume (m^3)
v	air valocity (m/s)
x	water content (kg/kg dry substance)
α	heat transfer coefficient ($W/m^2\ ^{\circ}C$)
β	mass transfer coefficient (m/s)
λ	thermal conductivity ($W/m\ ^{\circ}C$)
ν	kinematic viscosity (m^2/s)
ρ	density of humid air (kg/m^3)
ρ_o	product density (kg/m^3)
ρ_D	density of vapour (kg/m^3)
ρ_L	density of dry air (kg/m^3)
τ	time (s)
Nu	Nusselt number $\frac{\alpha \cdot \ell}{\lambda}$

Sh	Sherwood number	$\frac{\beta \cdot \ell}{D}$
Re	Reynolds number	$\frac{v \cdot \ell}{\nu}$
Pr	Prandtl number	$\frac{\nu}{a}$
Sc	Schmidt number	$\frac{\nu}{D}$
Le	Lewis number	$\frac{a}{D}$

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Figure legends.

Figure 1 Research convection oven.

Figure 2 Moisture content as a function of time.

Figure 3 Surface temperature as a function of time at 150°C.

Figure 4 Surface temperature as a function of time at 225°C

Figure 5 Heat transfer coefficient as a function of time

Figure 6 Mass transfer coefficient as a function of time

Figure 7 Log α as a function of log velocity at different
temperatures and humidities.

Convection oven frying I. Heat and Mass Transfer....

Table 1. Frying parameters

Air temperature ($^{\circ}\text{C}$)	150			225		
Air velocity (m/s)	5		9	5		9
Air humidity (t_w $^{\circ}\text{C}$)	45	87	45	45	97	45
Partial vapour pressure of the air bulk (10^{-5} N/m 2)	0.023	0.578	0.023	0	0.813	0
Saturation vapour pressure at wet bulb temperature (10^{-5} N/m 2)	0.097	0.625	0.097	0.097	0.908	0.097

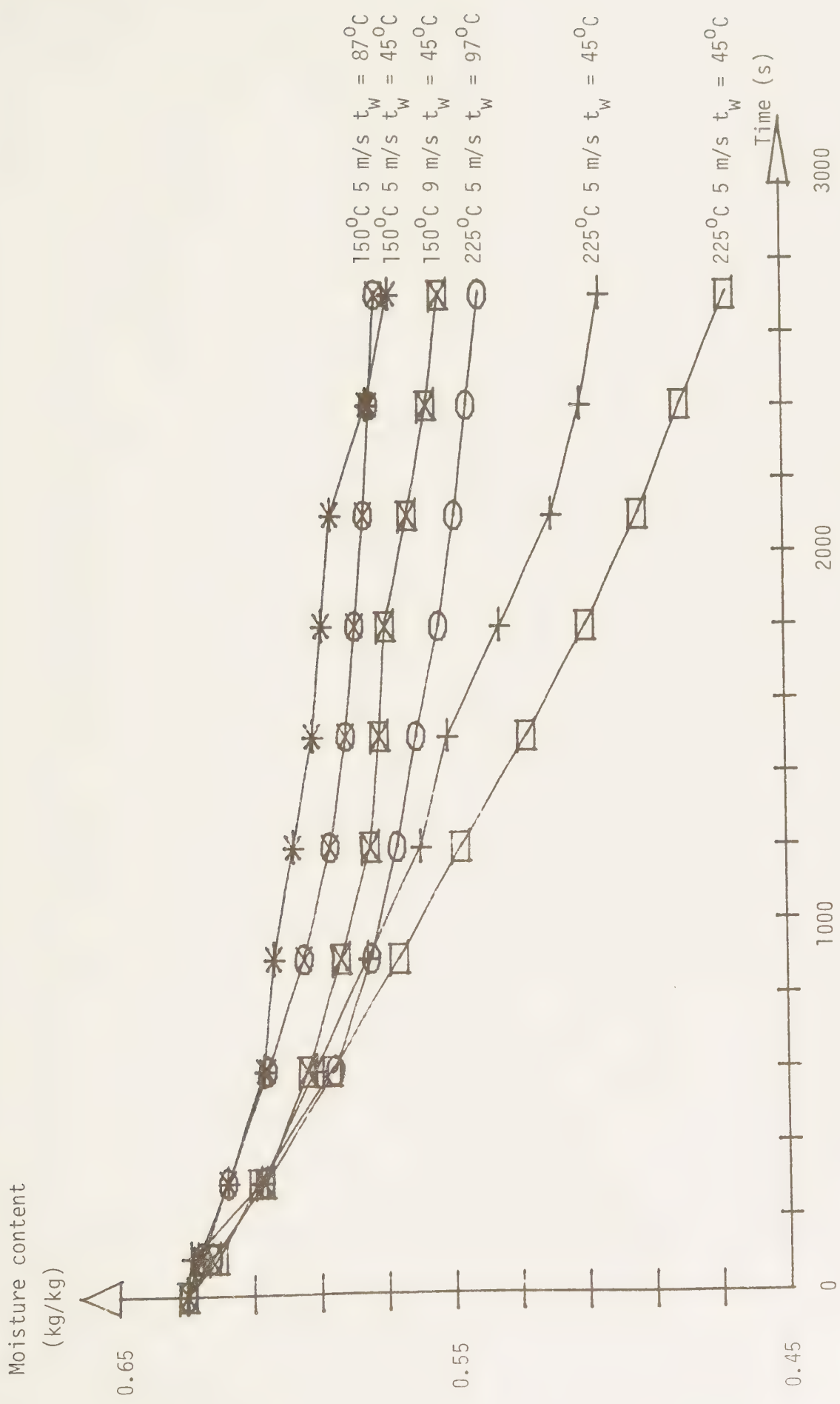
Table 2. Moisture loss rate no heading.

Moisture rate g/s Period	150°C			225°C		
	5 m/s dry air	5 m/s humid air	9 m/s dry air	5 m/s dry air	5 m/s humid air	9 m/s dry air
(1) "Constant rate"	0.090	0.077	0.125	0.120	0.120	0.160
(2) Falling rate (a)	0.038	0.044	0.048	0.080	0.050	0.100
(3) Falling rate (b)	0.016	0.017	0.020	0.030	0.020	0.060
Total mean value	0.040	0.040	0.040	0.060	0.050	0.080

Table 3. Surface water content no heading.

Water content (kg/kg crust)					
Period	5 m/s "dry" air	9 m/s "dry" air	5 m/s "dry" air	5 m/s humid air	5 m/s "dry" air
When temperature in the center was 70°C	0.020	0.017	0.015	0.030	0.014
After 45 minutes frying	0.017	0.016	0.011	0.020	0.010





Temperature ($^{\circ}\text{C}$)

200

150

100

50

0

9 m/s $t_w = 45^{\circ}\text{C}$
5 m/s $t_w = 45^{\circ}\text{C}$
5 m/s $t_w = 87^{\circ}\text{C}$

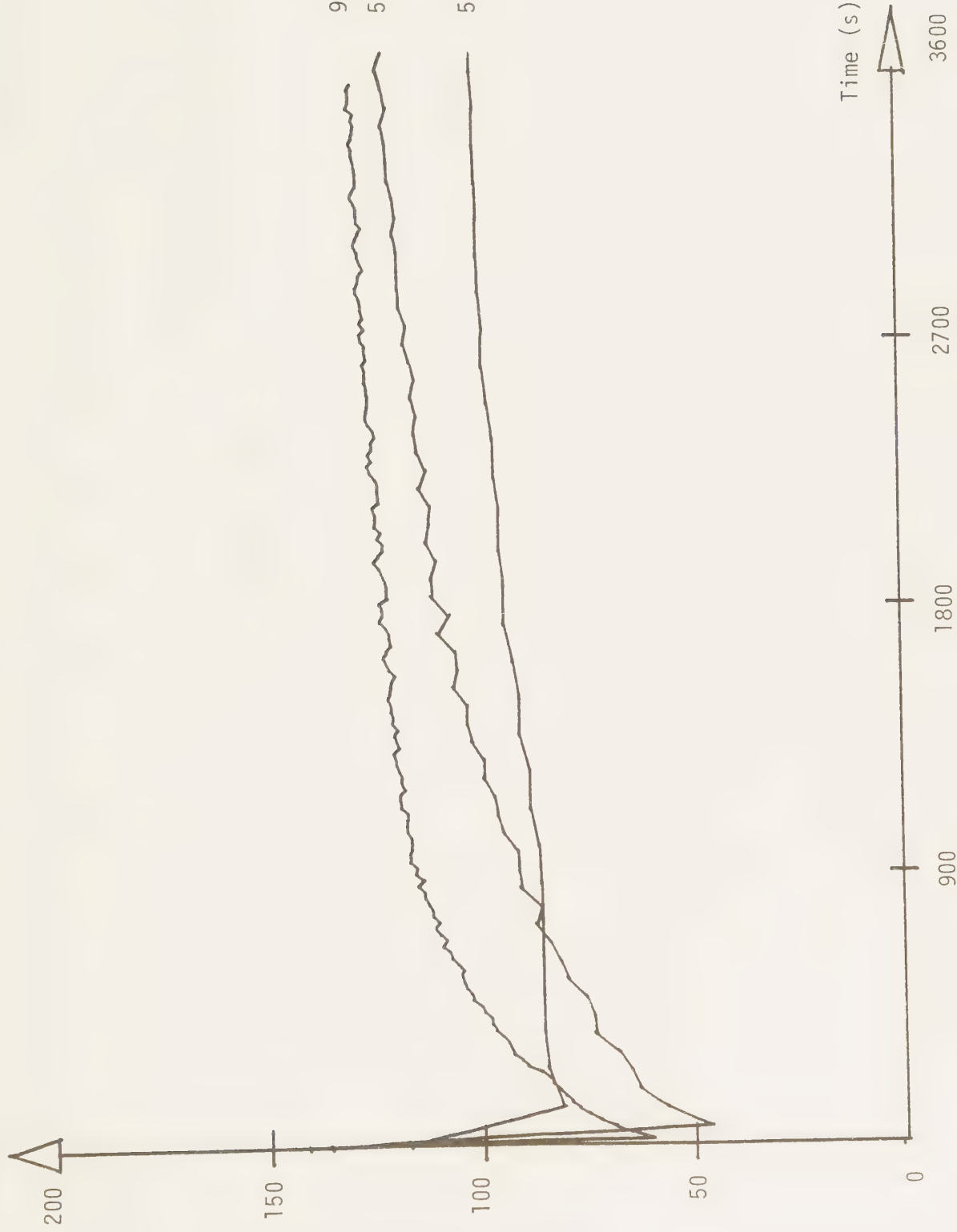
Time (s)

3600

2700

1800

900



Temperature ($^{\circ}\text{C}$)

200

150

100

50

9 m/s $t_w = 45^{\circ}\text{C}$

5 m/s $t_w = 45^{\circ}\text{C}$

5 m/s $t_w = 97^{\circ}\text{C}$

Time (s)

3600

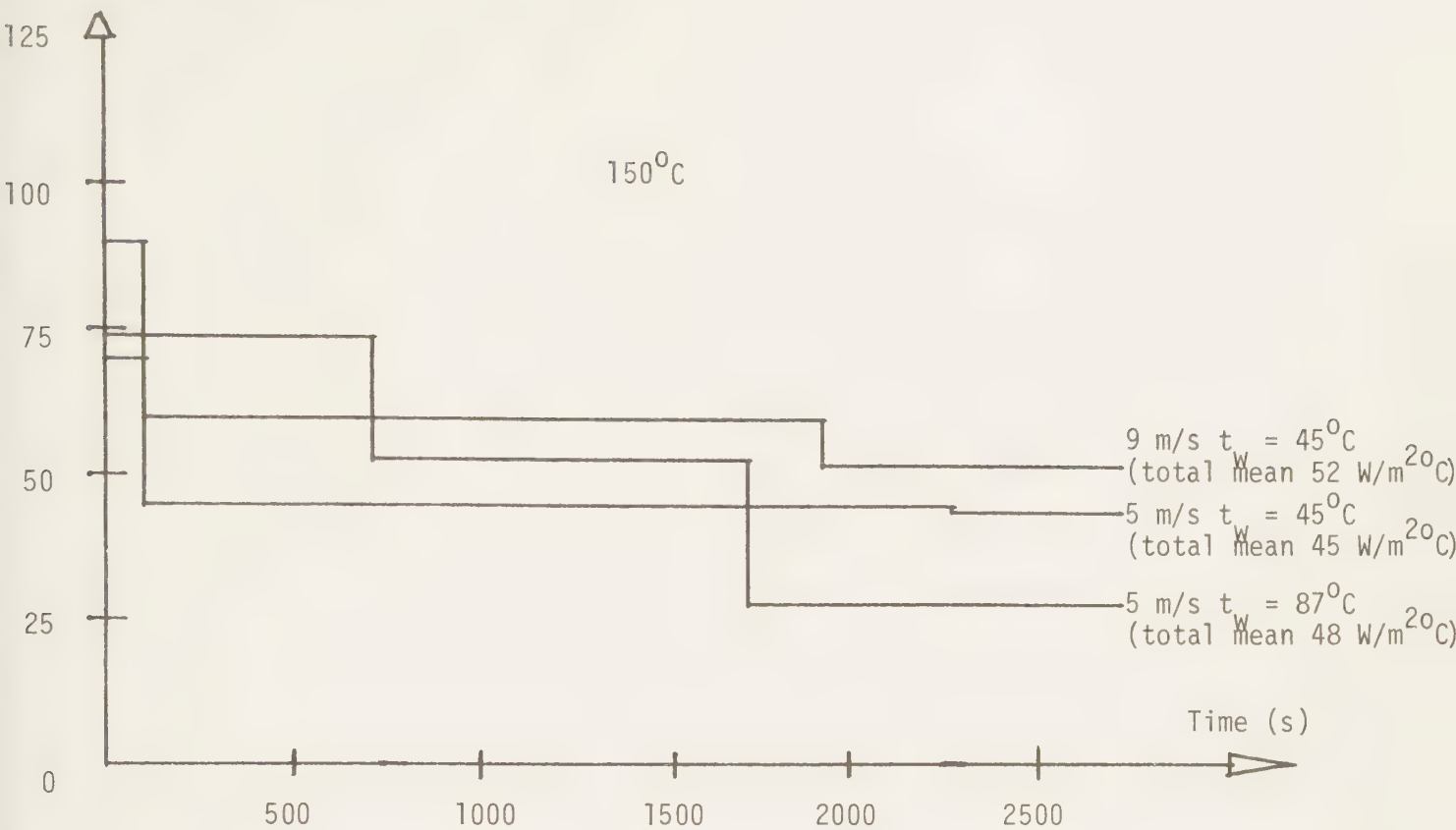
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1800

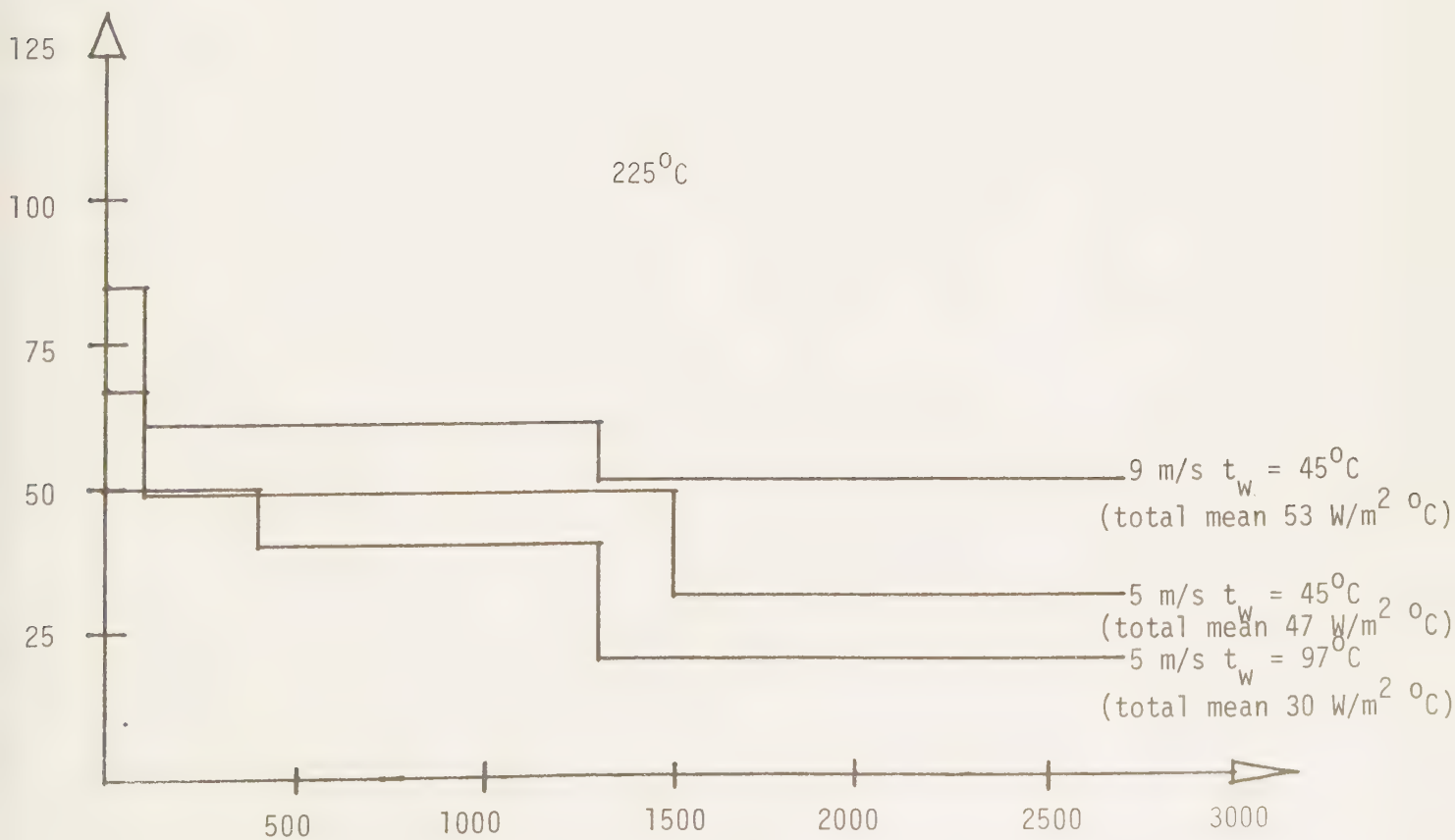
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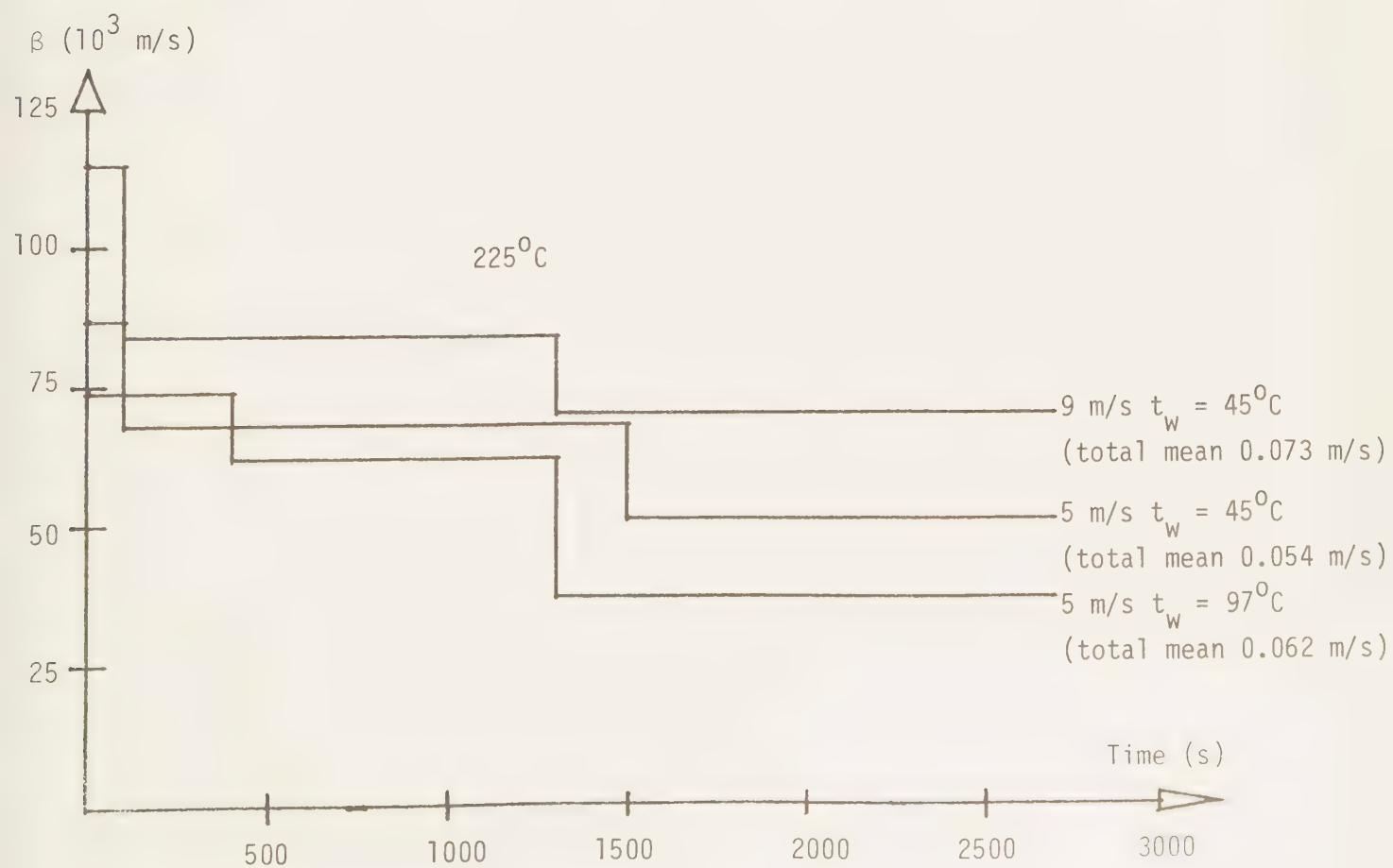
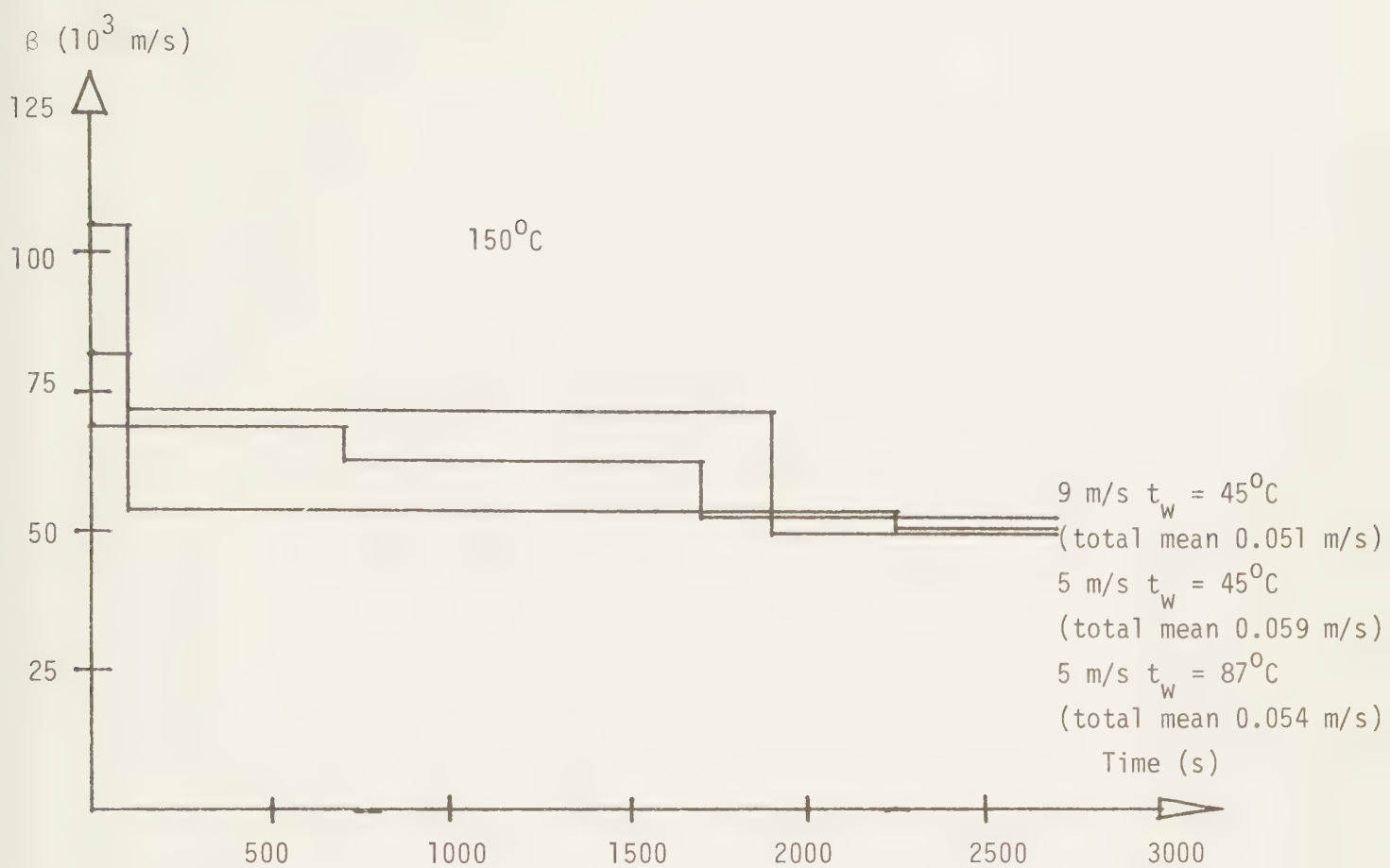


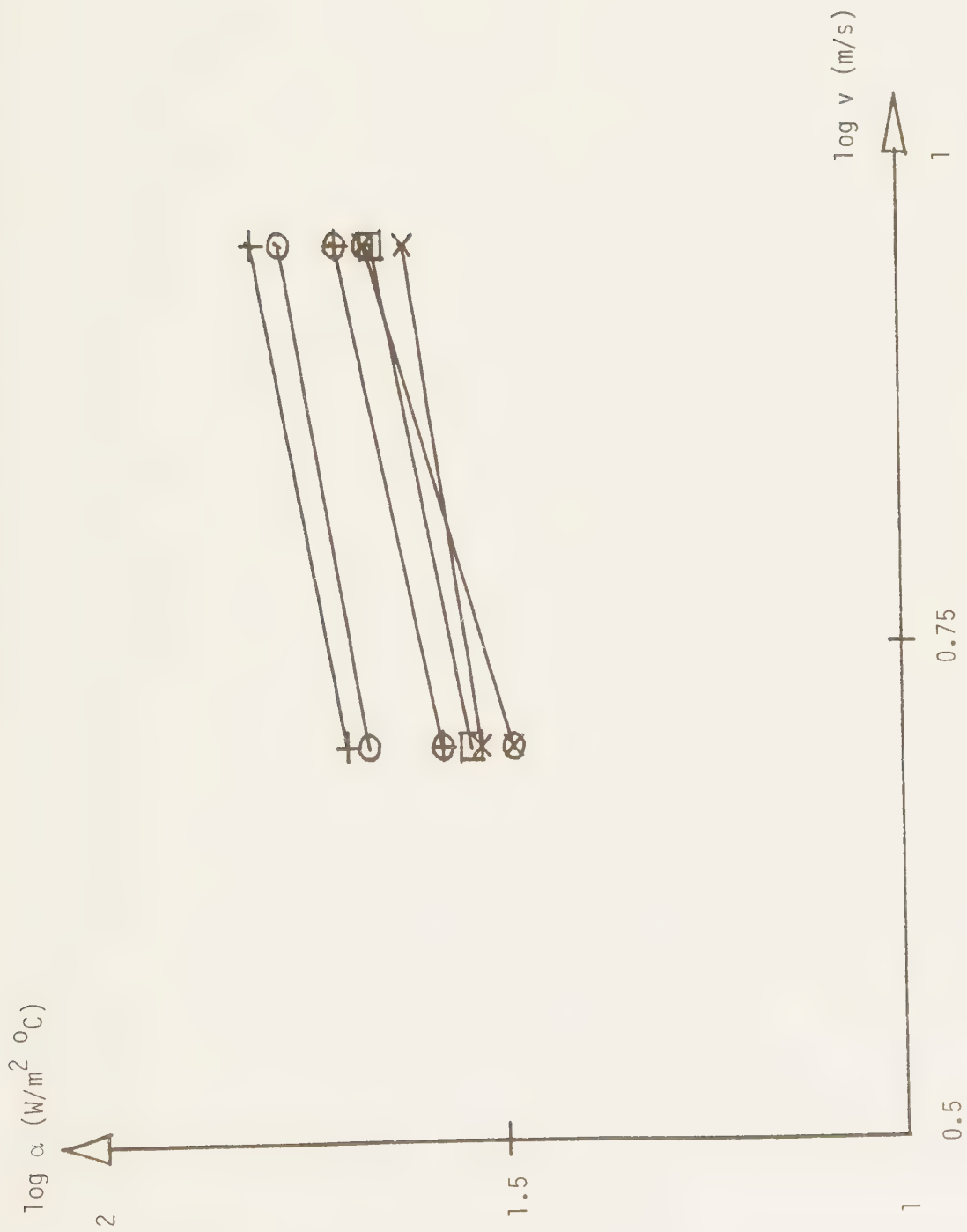
$\alpha \text{ W/m}^2 \text{ } ^\circ\text{C}$



$\alpha \text{ W/m}^2 \text{ } ^\circ\text{C}$







Abstract.

CONVECTION OVEN FRYING II. HEAT AND MASS TRANSPORT IN THE
PRODUCT.

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The different origins water losses from frying meat loaves in a specially designed convection oven are discussed. A theory is presented for how the water content inside the crust of what depends on the recipe. A model is developed for calculating water content profile in the crust and the thermal conductivity of the crust. Meat loaves of an industrial recipe were fried for one hour at different temperatures, humidities and velocities of the air. The water content of the crust was shown to be very low at a comparatively long distance from the surface and the profile was very steep close to the evaporating zone. The flow of water close to the evaporating zone could be changed when using different recipes of minced meat. When adding, for example, potato starch the water holding capacity (WHC) is increased and the main water losses occurs as evaporation.

Convection oven frying II. Heat and Mass transport in the product.

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Introduction.

To be able to calculate frying, cooking or reheating food products in a convection oven, the mechanisms of heat and mass transport in the product have to be known. This investigation deals with these phenomena as well as the heat and mass transfer between air and product, which have been discussed earlier (Skjöldebrand). Basic theories (Keey 1972; Krischer 1963; Lykow 1955; Kneule 1975) of drying have been applied in convection oven frying which is a drying operation at elevated temperatures.

All frying methods are accompanied by losses of water. In this study the different origins of the losses are discussed. Strongly connected with these losses is the formation of a crust. Moisture and temperature changes were studied in order to understand the chemical and the structural changes which characterize the crust. A model for calculating the water content profile in the crust, was made starting from the sorption isotherm (Harmathy 1969; Iglesias et al., 1976). Earlier work showed that water is expelled from the beef muscles because of protein denaturation at certain, time temperature treatments (Dagerskog 1978; Hamm 1977; Godsalve et al., 1977; Hung et al., 1978). This water holding capacity is studied for different recipes of minced meat products. From the results a theory is presented for how the water content inside the crust of meat loaves varies on different recipes.

Theory

In convection oven frying there is an exchange of heat and mass (water) between the air and the product. With regard to the transfer conditions three stages can be recognized. This has already been discussed in the previous paper (Skjöldebrand) and is only summarized here.

1. Preheating of the product surface from the initial temperature to the dew point.
2. Constant surface temperature, t_w . This is the constant rate period using drying terminology.
3. The surface temperature increases above the wet bulb temperature. This is known as the falling rate period.

Frying of meat products is signified by the formation of a crust. In this work the crust is defined as those parts of the product which have reached a temperature above 100°C , i.e. the parts situated outside the 100°C -isotherm. The crust has a moisture content remarkably lower than the initial moisture content and that of the inner part of the product (inside the 100°C -isotherm).

The main water evaporation takes place in the vicinity of the 100°C -isotherm even if the moisture content is continuously lowered also inside the 100°C -isotherm as well as in the crust itself. The product is a capillary-porous system with a wide range of capillary diameters. When water is evaporated,

the bigger capillaries are first emptied and later the smaller ones. Therefore, evaporation not only takes place along an isotherm but rather in a zone of a certain depth (Harmathy 1969). Temperature and moisture content profiles develop in principle according to fig. 1. In calculating these profiles the following premises and approximations have been taken.

1. All transport of water in the crust takes place as vapour i.e. the mass flow of vapour is proportional to the vapour pressure drop in the crust and inversely proportional to the thickness of the crust.
2. In the transport equation the mass of vapour refers entirely to the changed position of the 100°C -isotherm. The decrease of moisture content of the crust is neglected thus giving the same mass flow all through the crust.
3. The (partial) vapour pressure in the crust is at any moment supposed to be in equilibrium with the water content of the crust at actual temperature (Harmathy 1969). This equilibrium is defined by the sorption isotherm of the material under valid conditions. The vapour pressure at the 100°C -isotherm is supposed to equal the saturated vapour at this temperature ($a_w = \phi = 1$). At the surface and at any distance from the surface outside the evaporation zone is $\phi < 1$. The sorption isotherm at the relevant temperature gives this relation.

4. In the crust the product properties are changed because of heat denaturation. This means that sorption properties are also changed during processing and that the outer part of the crust has other properties than those parts close to the 100°C -isotherm. For each element (distance from the surface) the preceding time-temperature treatment is used to calculate a modified Arrhenius equation for the chemical changes. The change in sorption properties is supposed to be proportional to the corresponding integral.
5. From the flow of heat (water evaporation plus elevation of temperature inside the 100°C -isotherm) thermal conductivity of the crust is calculated. The resulting value is an average value as there is steep moisture content gradient in the crust.
6. Shrinkage is neglected.

Heat transfer inside the 100°C -isotherm is supposed to take place as conduction by means of an apparent thermal conductivity. A certain transfer of water is coupled to the heat transfer; this is noticed as an increased thermal conductivity (i.e. "apparent" thermal conductivity). It may in certain cases (depending on water holding properties of the product) also be observed as an increase in moisture content in the central parts of the product. Similar observations have been reported in the literature (Lisovenko et al., 1973; Auerman 1977).

The transport of water inside the 100°C-isotherm is supposed to take place only as capillary liquid flow. The moisture content profile therefore may be calculated by means of Fick's second law, for a plate and with constant diffusivity.

For certain product compositions, however, the water holding capacity (WHC) is influenced by the time-temperature treatment already before evaporation takes place. It has been shown that beef muscles at certain time-temperature combinations are denaturated in such a way that water (juice) is pressed out of the fibres (Dagerskog, 1978; Hung et al., 1978; Godsalve et al., 1977; Hamm, 1977). This means that the water holding capacity is decreased. It is significant for a pure meat product but in a mixture such as in the loaves containing potato starch etc, part of the water may be absorbed by these ingredients. This may influence the moisture content profile and give another break on the curve.

Materials and Methods

Apparatus and Samples

The convection oven used has been described earlier (Skjöldebrand). This oven is especially designed for investigation purposes.

Minced meat was formed in to loaves with the dimensions 200 x 50 x 50 mm. The recipe was one used in industrial processing containing ingredients which can absorb water. These meat loaves were used for temperature measurements during convection frying. To study the influence of water holding capacity

two different recipes were used. The first one was the same as the above mentioned and the second one only contained 80% meat and about 20% water. The composition of the two recipes are given in table 1.

Experimental Procedure.

1. Temperature measurements

Six different combinations of air temperature, air velocity and air humidity were used for frying according to Skjöldebrand. The meat loaves were placed in a teflon coated net cage to avoid deformation during frying. One of the shortest sides of the loaf was placed towards the air stream. Very thin thermocouples (total diameter 0.5 mm) of chromel-alumel were placed in the product at different distances from the surface and one thermocouple was placed in the center of the product. The surface temperature was measured by means of the IR-sensing head according to Skjöldebrand. The frying was carried out for one hour.

2. Measurement of sorption isotherms

A thin sample (~2 mm) of the industrial recipe product was fried in the convection oven for a long time. The reason for this was to get a piece of the sample that had the least moisture content and had reached a higher temperature than the crust. The temperature both on the surface and in the center reached 100°C fairly fast. The temperature increased after this almost linearly up to 180°C when the frying was stopped. It took 90 minutes to go from 100°C to 180°C. Another piece of the minced

meat sample was cooked in water until all of it reached 100°C

Sorption isotherms were measured for both the samples at 25°C and 45°C in a Sina Scope hygrometer (Karan-Djurdjic 1970).

Each measurement was repeated twice. From these isotherms a sorption isotherm at 180°C for fried meat and one at 100°C for cooked meat were extrapolated.

3. Analysis of water holding capacity. (Dagerskog 1978).

In order to calculate the water losses due to protein denaturation in the product, the water holding capacity of the two recipes were determined. Raw minced meat (10 grams) was placed in plastic pouches, vacuum sealed and pressed to 2 mm thickness. The pouches were dipped into thermostated waterbaths of given temperatures for a given time. Each time-temperature combination was repeated four times. After heating, the pouches were cooled and drained for 1 minute on absorbent paper and the sample was analysed for fat and water content.

Calculations

1. Temperature profile in the crust.

When the surface temperature had passed the wet bulb temperature and the falling rate period had started, the first critical point had been reached (Lykow 1955). Analysing the temperature curves in the falling rate period, it could be seen that these level out at 100°C or near 100°C . This point is called the

pseudo wet bulb temperature (Keey 1972). After a while at this point the temperature increased towards the air temperature. The time when this temperature increase started, at a certain distance from the surface, indicated when the evaporating zone was passing. By means of thermocouples placed at different distances, the growth of the crust could then be calculated.

From known data about where the thermocouples were placed and the temperatures at these points, the temperature profile in the crust could be determined.

From the above mentioned results, the time-temperature relationship in the crust could be determined. This relationship is assumed to be linear in each point of the crust.

2. Model for calculating the sorption isotherm at different temperatures and different degrees of chemical degradation.

The sorption isotherms for the two samples of different frying degrees were plotted. Knowing two isotherms of each sample a modified Halsey equation (Iglesias 1976) was used to derive an equation for temperature dependence. These equations and the sorption isotherms obtained at 25°C and 45°C are shown in fig. 2.

3. Water activity and water content of the crust.

From the earlier paper (Skjöldebrand) the surface water vapour pressure and the surface water activity were determined. Two

suppositions were made 1) the water activity at the evaporating zone was assumed equal to 1, and 2) the mass flow of vapour was assumed to be proportional to the vapour pressure drop in the crust.

From these assumptions and the surface water activity the water activity at each point of the crust was calculated since the sorption isotherm and the water activity are known, the water profile in the crust could be determined in the following manner.

- a) The sorption isotherm at 180°C (figure 3).
- b) The sorption isotherm of the cooked sample heated to 100°C was determined at 100°C (figure 3).
- c) The degree of denaturation and thus the decrease in sorption properties was assumed to be proportional to a modified Arrhenius equation for the valid heat treatment (Hallström et al., 1977) (figure 3).
- d) The time temperature relationship at each actual point in the crust was determined.
- e) From the modified Arrhenius equation and the temperature, the water content at the actual point was determined.

4. Determination of thermal conductivity of the crust.

From data in the earlier paper (Skjöldebrand 1979) on heat transfer coefficient and surface temperature the thermal conductivity of the crust could be calculated according to Krischer (1963)

$$\frac{\lambda}{\ell_c} (t_s - 100) = \alpha (t_a - t_s)$$

The thermal conductivity was calculated at two different times (Skjöldebrand); 1) when the center had reached 70°C, which will characterize the ready made product, and 2) after 45 minutes of frying.

Results

1. Temperature in the product and growth of the crust.

Figures 4 to 9 show the time/temperature relationship at different points in the product. For each point under the surface it can clearly be seen how the temperature is leveling out at 100°C. In figure 10 the position of each point in the different samples are plotted against the time for the temperature increase above 100°C. In this way a linear relationship for the growth of the crust was shown. At 225°C and 9 m/s dry air the crust was formed and grew fastest. At humid air the growth was a little bit slower than at dry. Figure 11 and 12 shows the temperature profile of the crust when frying at 225°C, 9 m/s dry air and 150°C, 5 m/s dry air. These temperature profiles were calculated for two different times

1) when the center of the product had reached 70°C.

2) after frying in 45 minutes.

2. Moisture content of the crust.

The crust at the two different times were divided into ten parts. The results showed that the water activity was very low on the surface due to high surface temperatures and high mass transfer to the air. Figure 11 shows the water content profiles. The water content was very low at a comparatively long distance from the surface and the profile was very steep close to evaporating zone.

3. Thermal conductivity of the crust.

Table 2 shows the "Apparent" thermal conductivity of the crust for the six different frying experiments. These values are mean values over the whole thickness of the crust. As the local value is proportional to the temperature gradient (the flow of heat is assumed constant) the λ -values varies with the temperature profiles in the crust. The thickness of the crust is also shown at the two different times mentioned before.

4. Water holding capacity.

Figure 12 shows the water holding capacity for the two different recipes used. For the recipe with almost pure meat there is an evident loss of water at temperatures between 40 and 70°C. The other recipe however lost hardly any water at all for the actual temperatures.

Discussion.

Hung et al., (1978) have explained the flow of water migration in meat muscles during cooking. When using different recipes of minced meat this flow could be changed. When adding, for example, potato starch the water holding capacity is increased and the migration stops until evaporation starts. Most of the water losses, when frying of industrial minced meat product, seems to be due to evaporation in the crust. The water profile is very steep in the crust, which is at the same time very thin, and the temperature profile is also very steep over this zone. It must be borne in mind that the composition of the product has a great influence on these phenomena.

The surface water content decreases very rapidly after the constant rate period. As the moisture content is low and the temperature is high, chemical changes such as Maillard reaction takes place and this changes the sorption properties.

The final moisture content is determined by the sorption isotherms. Since the water holding capacity changes depending on the ingredients of the product sample, the moisture content inside the evaporation zone changes. This means that the water content near this zone is close to the original one when using a recipe with good water holding capacity. According to Iglesias et al., (1976) the modified Halseys equation used in this investigation is valid for $a_w = 0.1-0.8$. This means that at the surface and near the evaporation zone there could be some uncertainty in the moisture content values calculated.

The evaporation of the water takes place within a zone in the product which moves continuously. The corresponding pseudo wet-bulb temperature, here 100°C , stays for longer and longer time the nearer the center the evaporation zone reaches. This depends on the continuously increasing resistance against heat transfer from and vapour transport towards the surface.

Table 3 gives a summary of the water migration and temperature changes in minced meat products during convection oven frying. The product is divided into the different zones where different types of water and heat transports can take place.

At the start the whole product has the same moisture content, but eventually there is a slight increase due to migration of water towards the center (Auerman 1977). As the heat is transported from the air to the surface and towards the center, the temperature due to non-stationary heat transfer increases (Carslaw et al., 1959) and three different zones are formed. When the surface has reached 100°C a crust is formed. Inside the crust there is a zone where protein denaturation takes place and the physical properties are changed. In this zone nothing except, perhaps, a slight increase in water content has happened.

The migration of water in the product is a non-stationary transfer of liquid water. The moisture profile may be calculated according to Fick's law. However, this profile is dependent on the water holding capacity of the meat product. Certain premises have to be made to calculate the moisture profile in these materials (Carslaw 1959).

The water transport through the crust occurs as vapour diffusion in a capillary-porous material (Krischer 1963). The moisture profile in this part depends on the sorption isotherm, the degree of denaturation and chemical changes. To be able to determine this profile one has to presume that at each moment equilibrium takes place (Harmathy 1969).

After the surface has reached 100°C it is possible to estimate heat transfer in the product as conduction. The center of the product is heated through non-stationary heat transfer, with 100°C as constant driving temperature and the geometry is constant, thus neglecting the thickness of the crust. (Sörenfors 1978). During this period a high heat transfer coefficient is of minor importance as the main resistance to heat transfer is inside the product.

Table 3. A model of water migration and temperature changes during convection oven frying.

Zone	Boundary layer $\dot{Y} > Y_s$	Crust $Y_s > Y > Y_c$		Protein denatured $Y_c > Y > Y_{den}$	Protein undenatured $Y_{den} > Y > 0$
Transfer of water	Convection	Diffusion of vapour in capillary porous material		Non-stationary transfer of liquid	-
Water content profile	Depending on flow conditions	Depending on the sorption isotherm being a function of temperature and degree of denaturation		"Remaining water" according to water holding capacity at actual temperature	Original, a slight increase is due to transfer of vapour towards the centre.
Transfer of heat	Convection	Evaporation heat plus latent heat of internal product parts. Non-stationary heat transfer.		Latent heat. Non stationary heat transfer	
Temperature profile	Depending on flow conditions	Calculation of heat transfer in combination with water transfer $t_s > t > t_c$		Non-stationary heat transfer $t_c > t > t_{den}$ ($t_c = 100^{\circ}\text{C}$)	$t_{den} > t$

Nomenclature

a_w	water activity
l_c	thickness of the crust
p	pressure (N/m^2)
t	temperature ($^{\circ}C$)
t_c	temperature of the crust ($^{\circ}C$)
t_s	temperature of the surface ($^{\circ}C$)
t_{den}	denaturation temperature ($^{\circ}C$)
t_w	wet bulb temperature ($^{\circ}C$)
t_a	temperature of the air ($^{\circ}C$)
x_g	moisture content (kg/kg)
x_{g100}	moisture content at a temperature of 100° (kg/kg)
x_{gs}	moisture content of the surface layer (kg/kg)
x_{go}	initial moisture content (kg/kg)
y	loaf thickness related from the center (m)
y_s	thickness from the center to the surface (m)
y_c	loaf thickness from the center to the crust (m)
y_{den}	loaf thickness from the center to the denaturated part (m)
α	heat transfer coefficient ($W/m^2, ^{\circ}C$)
λ	thermal conductivity ($W/m, ^{\circ}C$)
τ	time (s)
ϕ	relative humidity

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Figure legends

Figure 1. Developed temperature and moisture content profiles.

Figure 2. Sorption isotherm at 25°C and 45°C for "boiled" meat and crust. □ Experimental values at 45°C. x Experimental values at 25°C - calculated from the modified Halsey equation.

Equation for boiled meat $a_w = \exp(-e^{-0.029 \cdot T - 2.16} \cdot x^{-0.0067 \cdot T - 0.91})$.

Equation for crust $a_w = \exp(-e^{-0.033 \cdot T - 2.92} \cdot x^{0.0043 - 1.99})$.

Figure 3. Sorption isotherm for boiled and fried meat used for water content calculations.

Modified Arrhenius equation $\ln \frac{x}{x_{100}} = k' \int_0^{\tau} (t(\tau) - 100) \cdot d\tau$.

Figure 4. Surface and product temperature at 150°C, 5 m/s and $t_w = 45^\circ\text{C}$.

Figure 5. Surface and product temperature at 150°C, 5 m/s, and $t_w = 87^\circ\text{C}$.

Figure 6. Surface and product temperature at 150°C, 9 m/s, and $t_w = 45^\circ\text{C}$.

Figure 7. Surface and product temperature at 225°C, 5 m/s, and $t_w = 45^\circ\text{C}$.

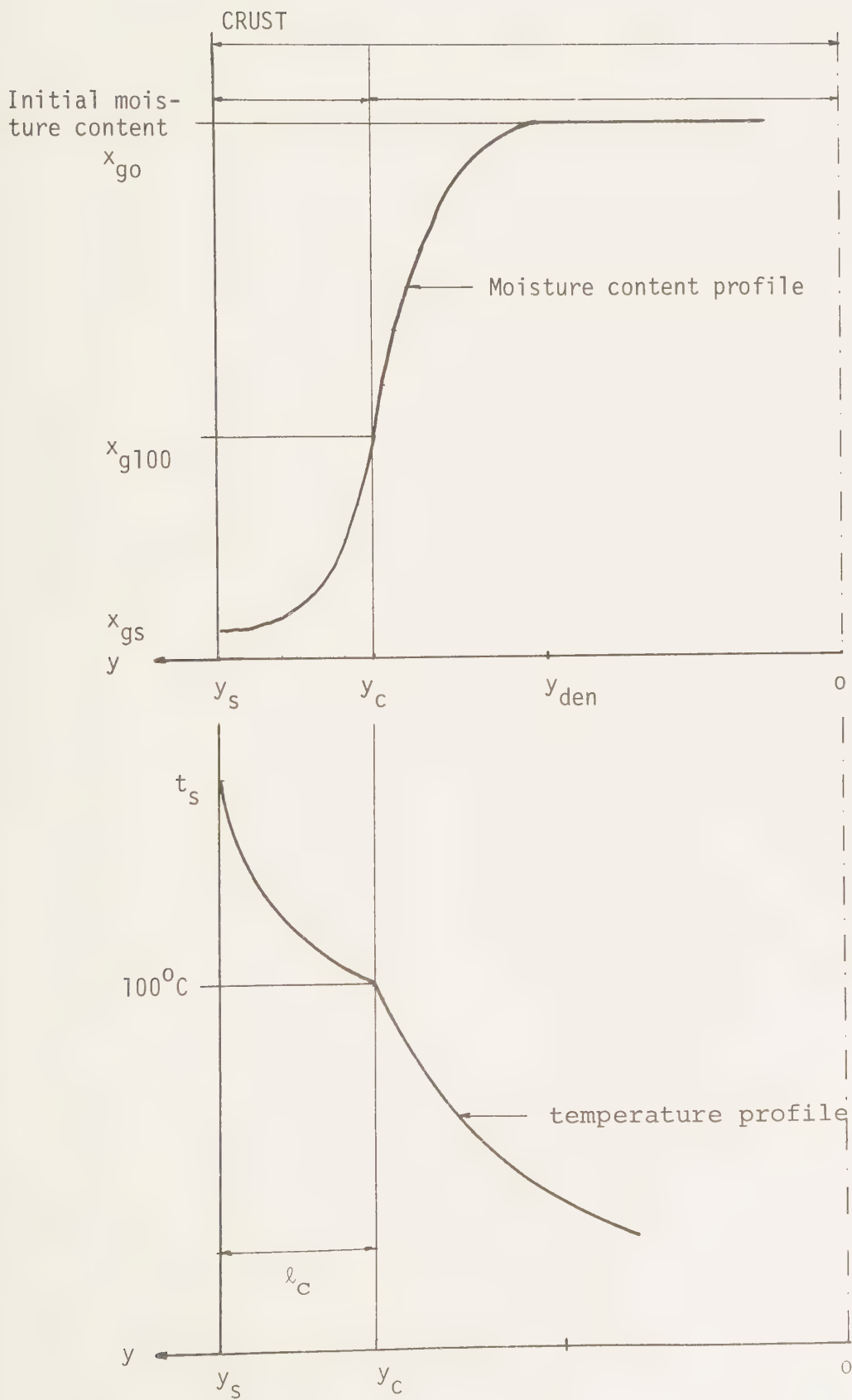
Figure 8. Surface and product temperature at 225°C, 5 m/s, and $t_w = 97^\circ\text{C}$.

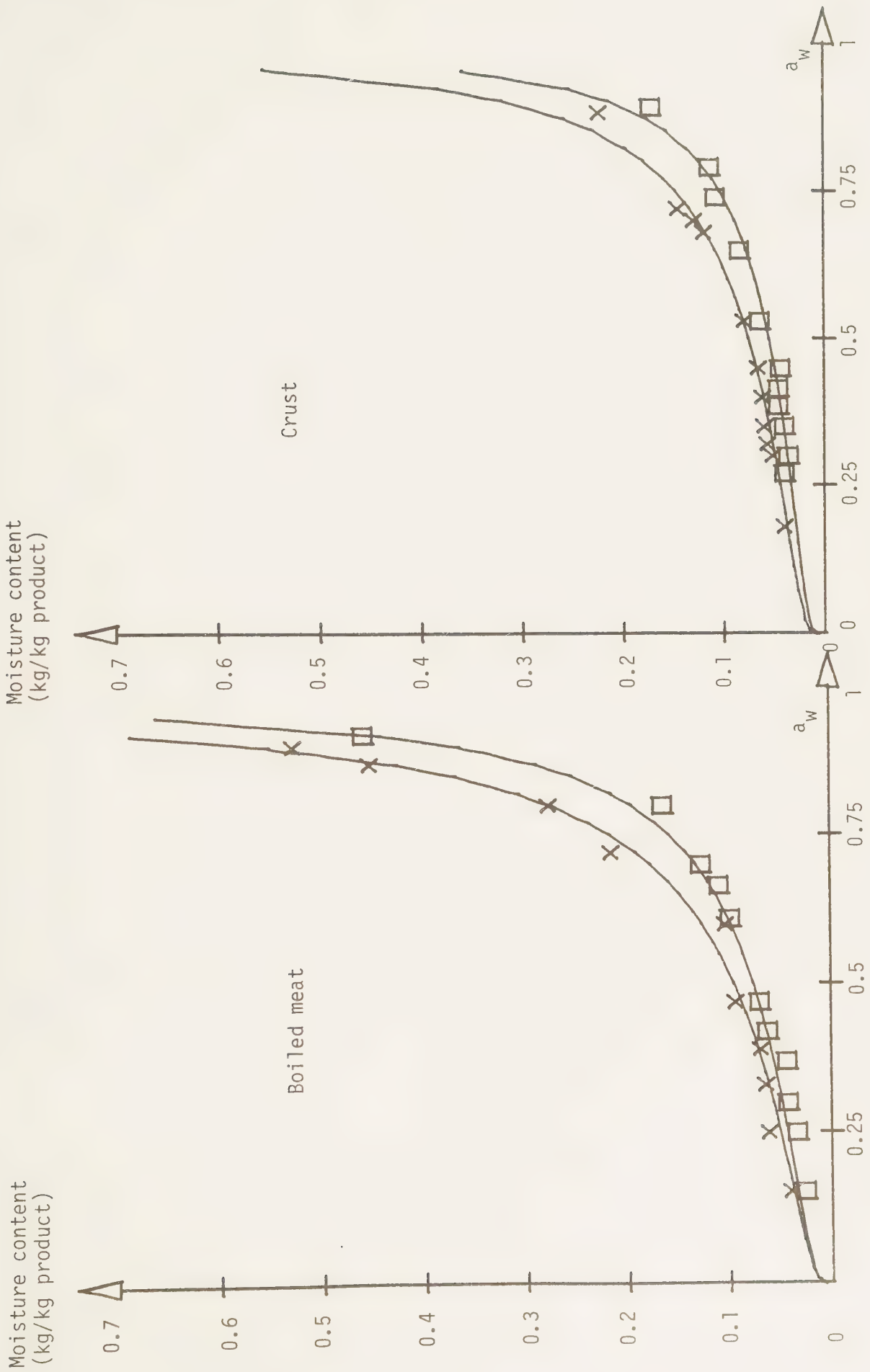
Figure 9. Surface and product temperature at 225°C, 9 m/s, and $t_w = 45^\circ\text{C}$.

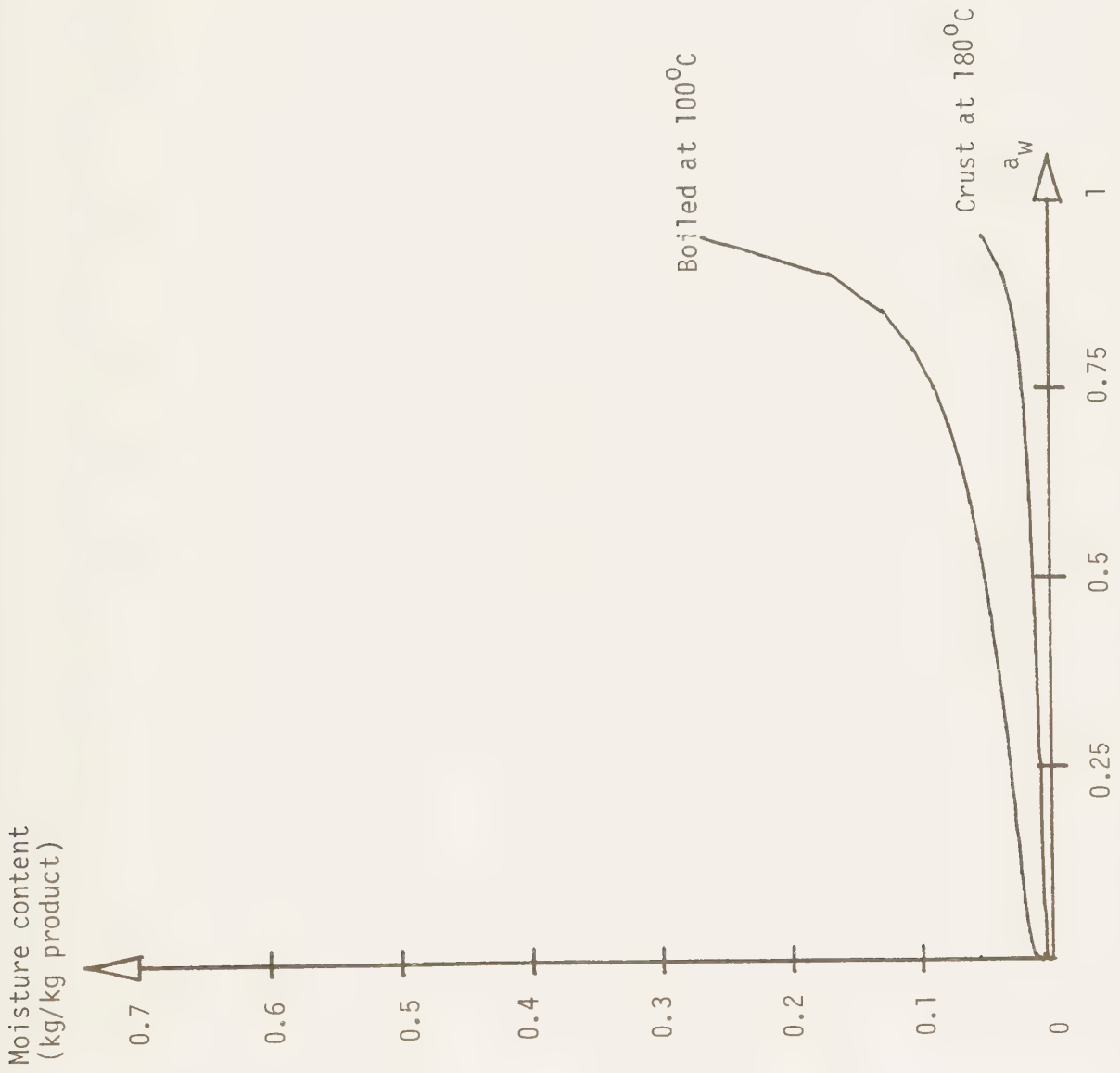
Figure 10. The depth of the crust as a function of time.

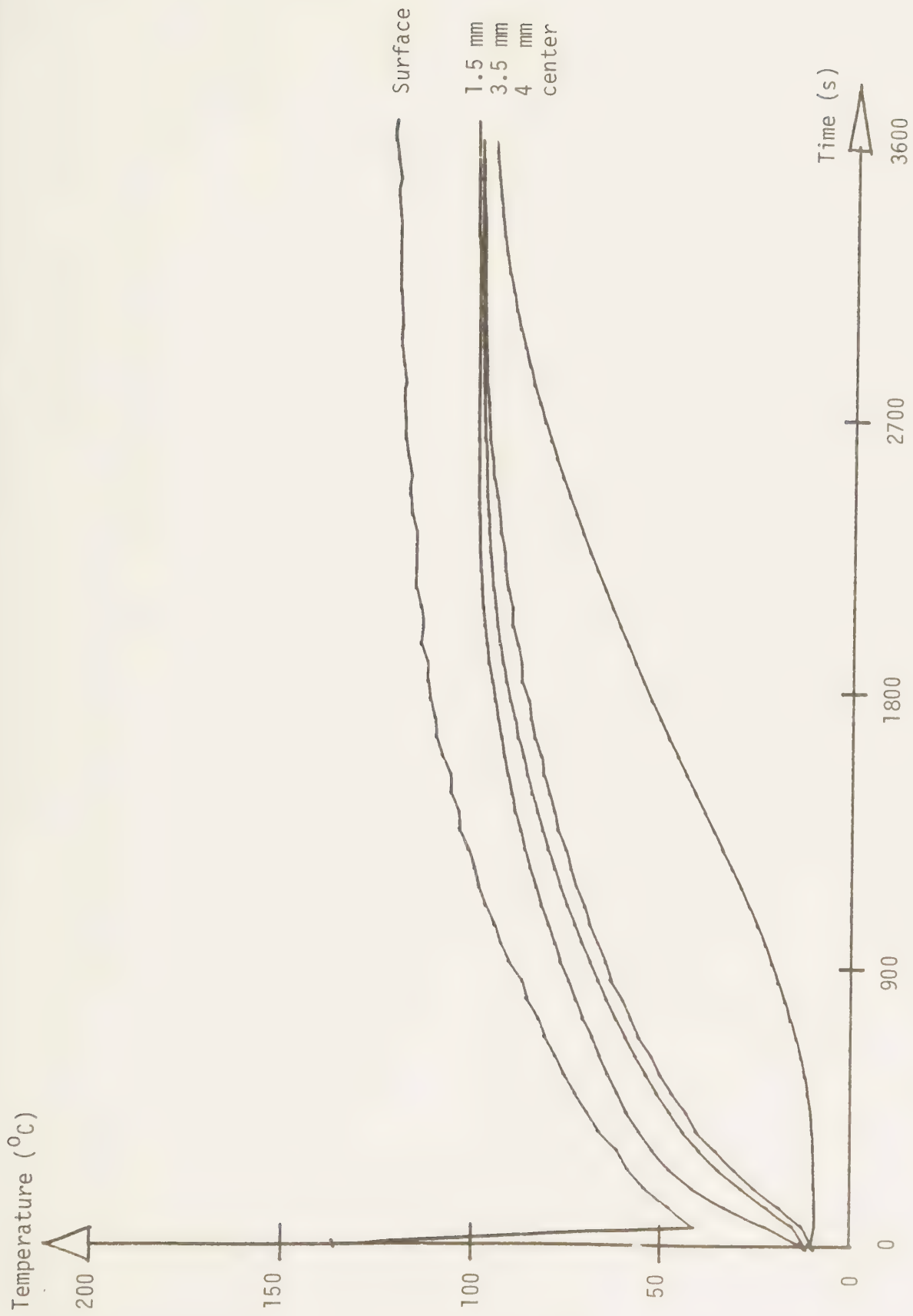
Figure 11. Temperature and moisture content of the crust as a function of crust thickness. 1. 150°C , 5 m/s, $t_w = 45^{\circ}\text{C}$, after 2300 s. 2. 150°C , 5 m/s, $t_w = 45^{\circ}\text{C}$ after 2700 s. 3. 225°C , 9 m/s, $t_w = 45^{\circ}\text{C}$ after 1300 s. 4. 225°C , 9 m/s, $t_w = 45^{\circ}\text{C}$ after 2700 s.

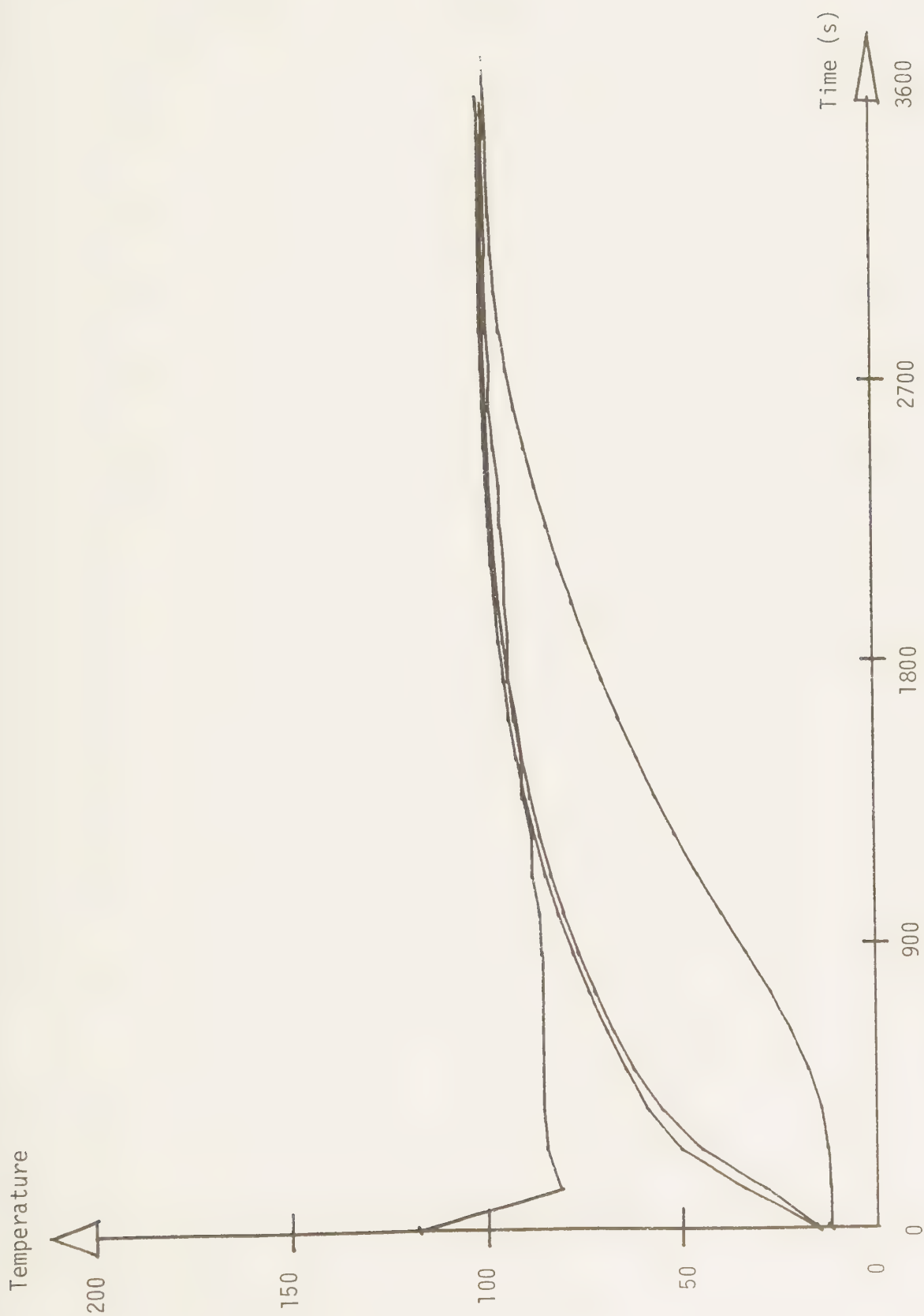
Figure 12. Water holding capacity (WHC) of two different recipes as a function of temperature.

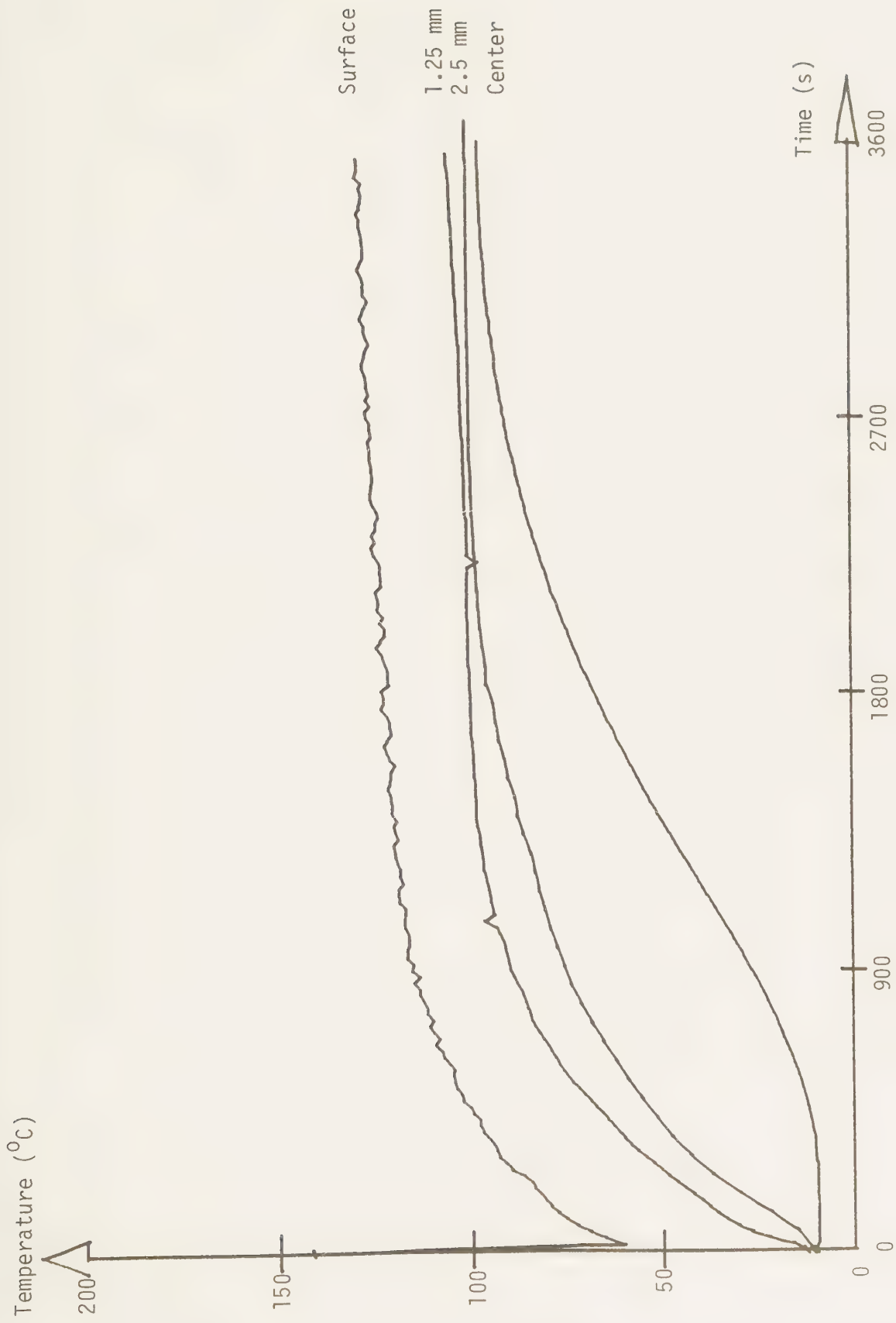


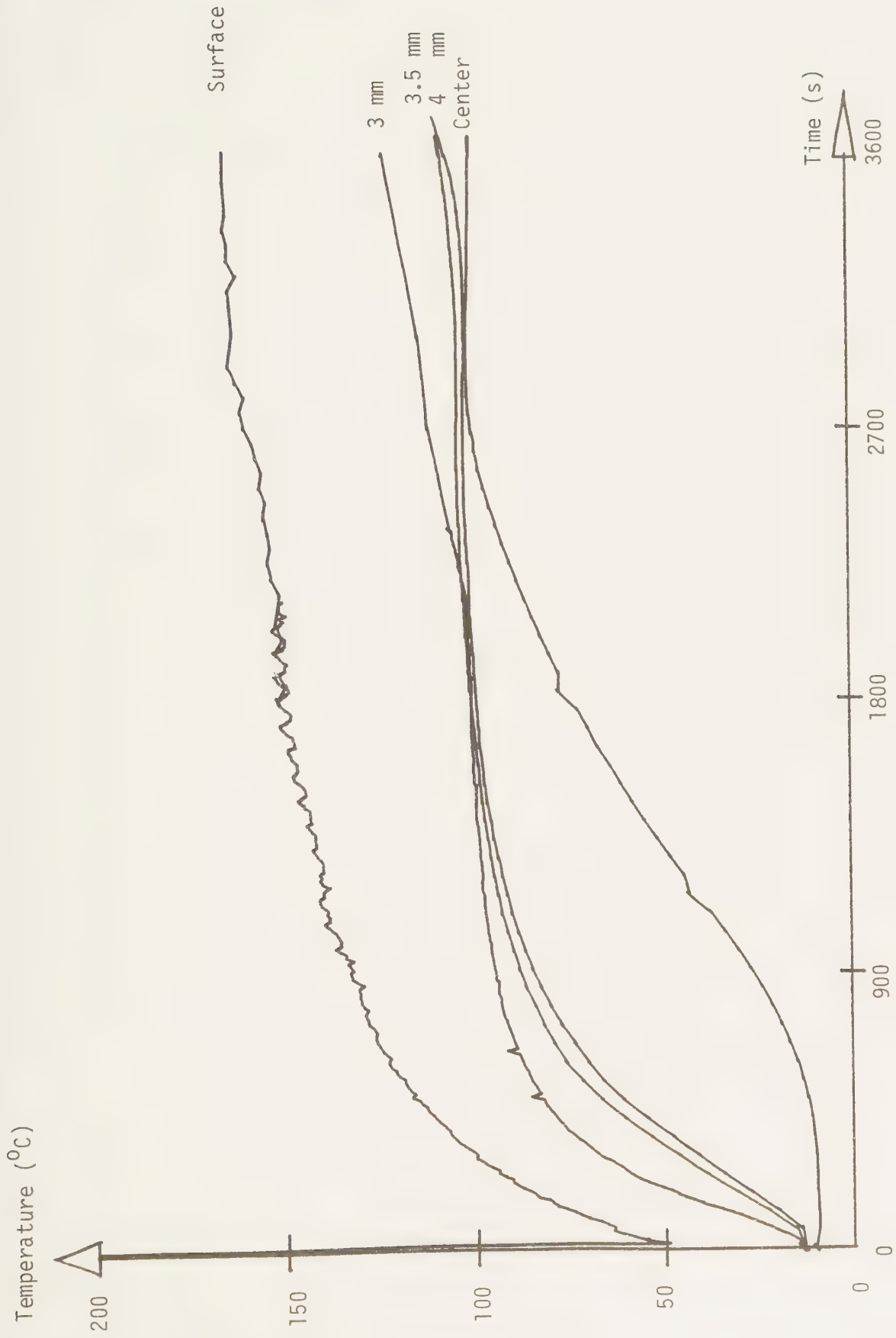


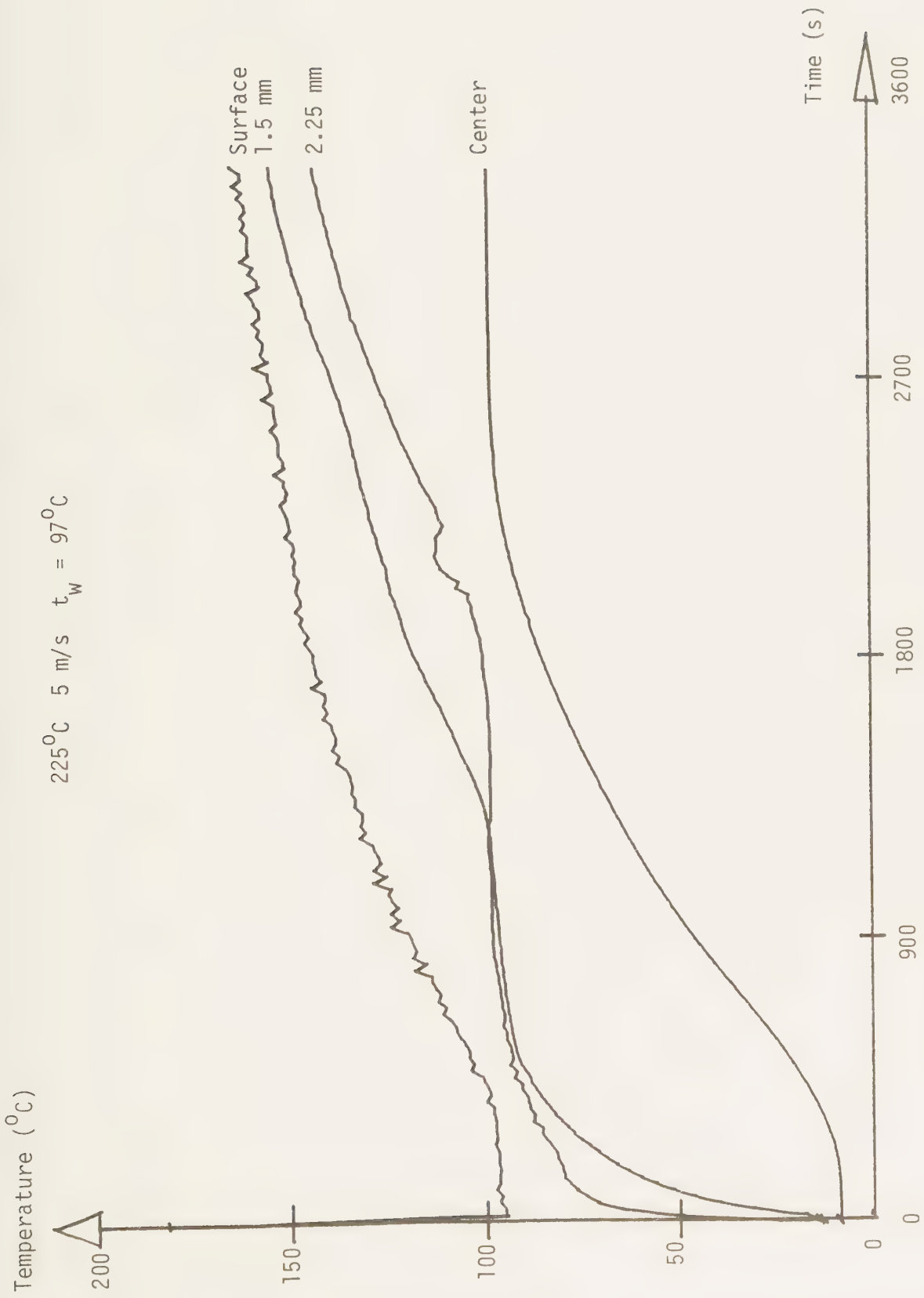


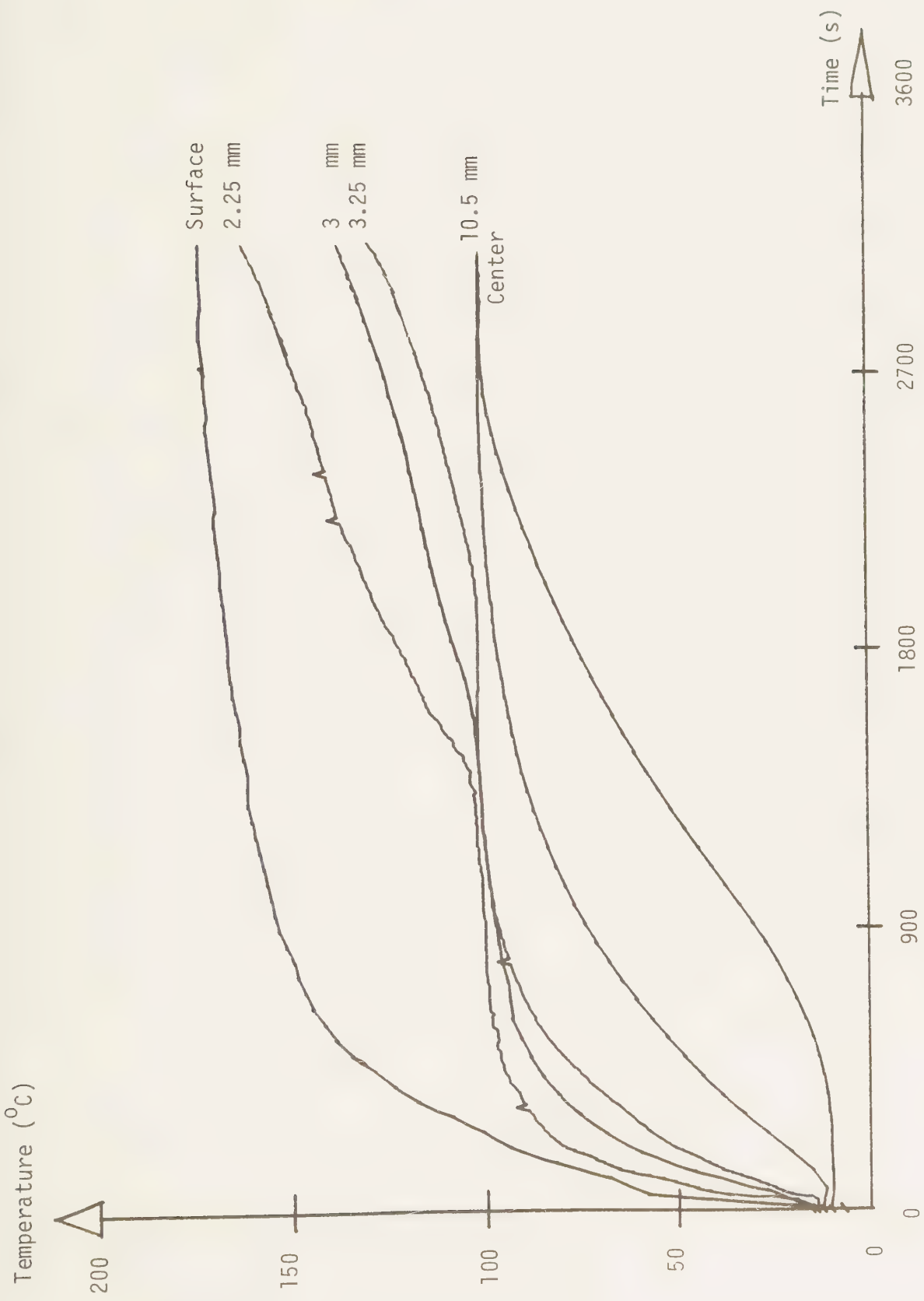






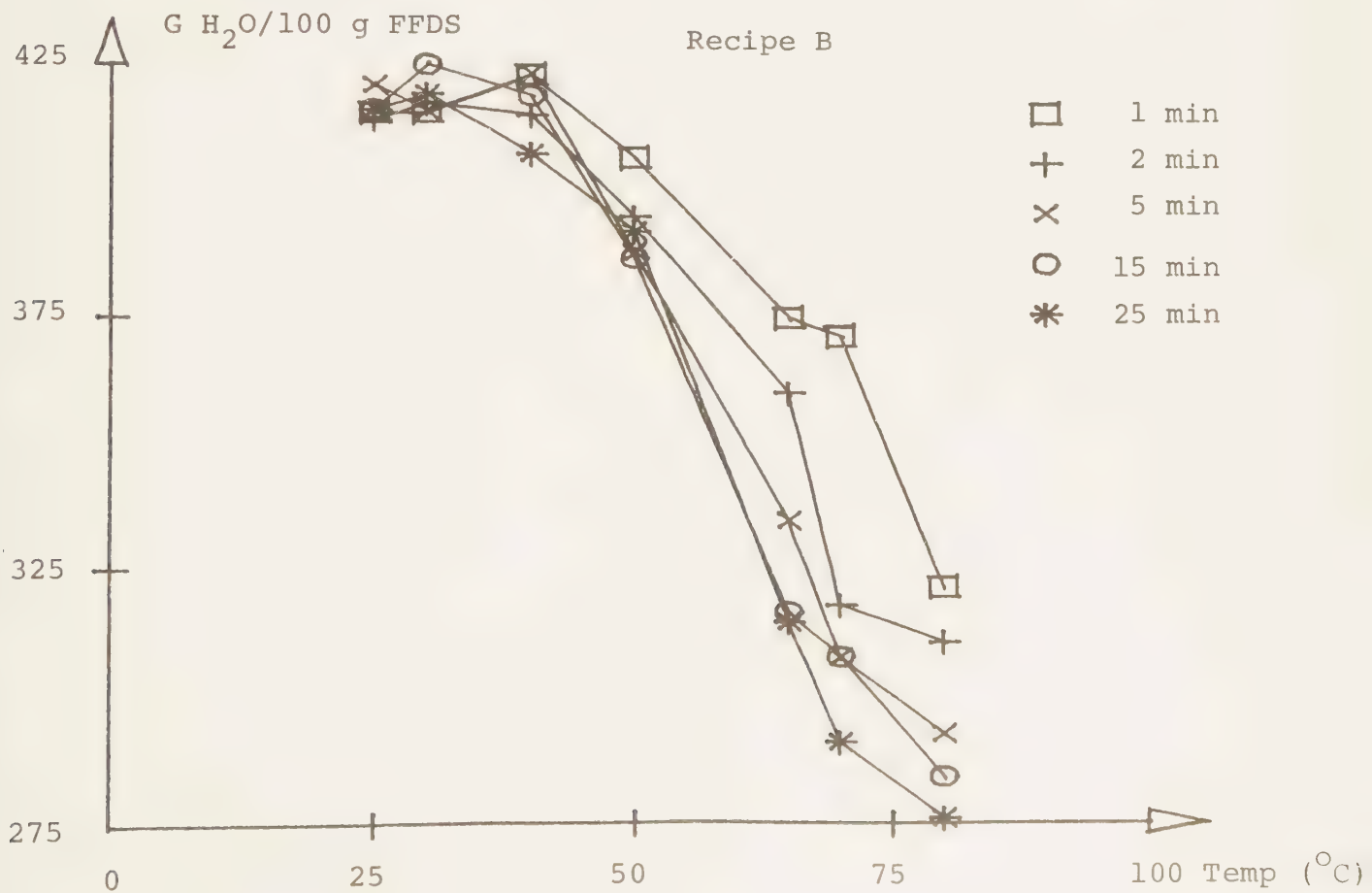
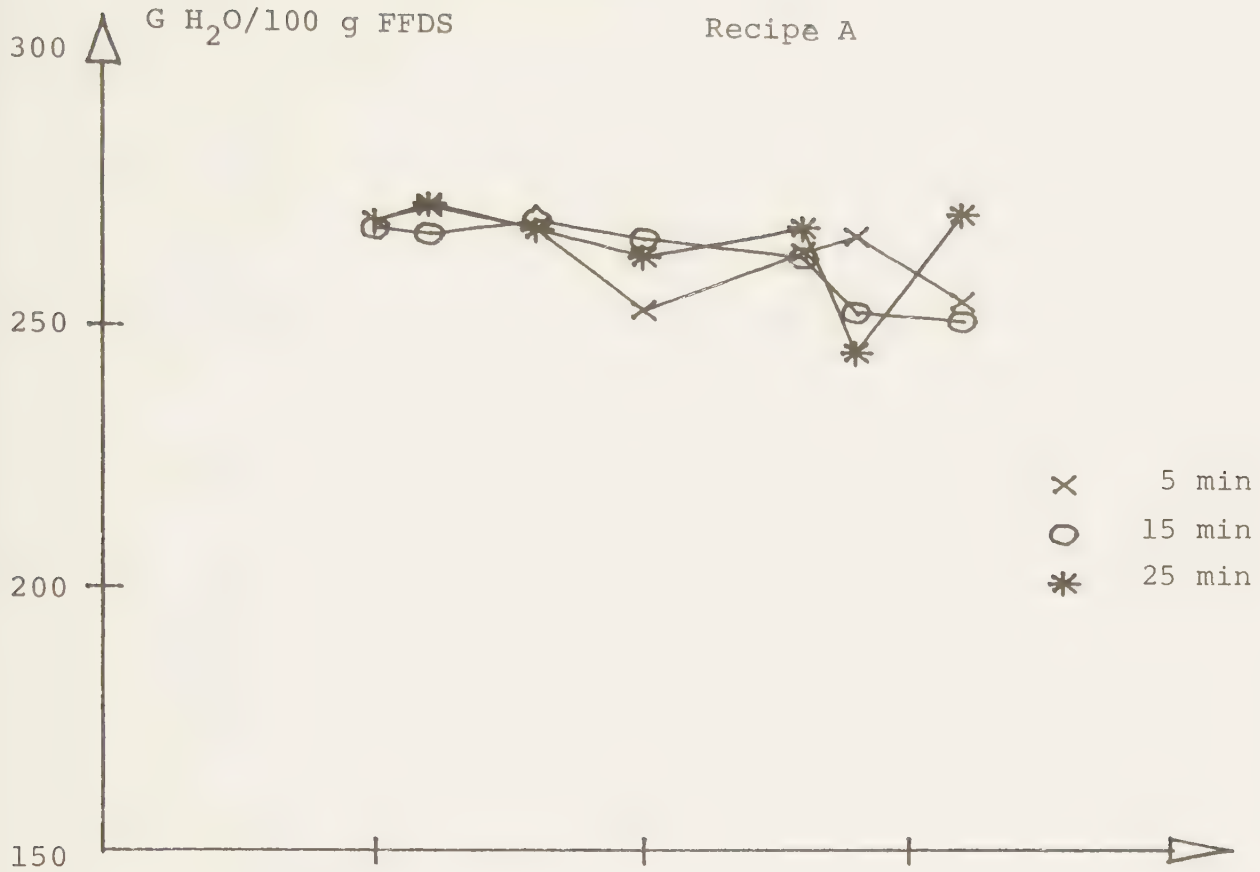












Convection oven frying II. Heat and mass transport.....

Table 1. The composition of the two recipe used.

	Water	Fat	Fat Free Dry Substance (FFDS)
Recipe A	63%	13.1%	23.9%
Recipe B	65%	19.1%	15.9%

Table 2. Thermal conductivity of the crust.

λ (W/m °C)		150°C				225°C	
Period		5 m/s dry air	5 m/s humid air	9 m/s dry air	5 m/s dry air	5 m/s humid air	9 m/s dry ai
2) When the tempera- ture in the center was 70°C		0.09	-	0.09	0.21	0.16	0.19
3) After 45 minutes frying time		0.09	-	0.09	0.24	0.08	0.26

CRUST FORMATION DURING FRYING OF MINCED MEAT PRODUCTS.

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Introduction

Frying of meat products is among other things, characterized by coagulation of proteins and giving a brown coloured crust. The crust is formed by chemical and structural changes at high temperatures. These phenomena have not been completely investigated, but it is known that the Maillard reaction plays an important role (1) and this involves a reaction between a reducing sugar and an amino acid under special conditions (2). Some investigations have been made to explain heat and mass transports in this area (3,4,5). A research project has been started in Sweden the aim of which is to explain the reactions that take place in the crust and their importance for the nutritional value and for the frying process. This investigation gives the first results from the project. Time - temperature relationship has been studied and the thickness of the crust has been calculated and followed by means of microscopic studies of the product.

The investigation is limited to frying in a convection oven and one recipe of minced meat specially made for the purpose was used.

Theory

In this research work the crust is defined as those parts of the product which have reached a temperature above 100°C . (5). Measuring the time-temperatures close to the surface it is found that the temperature raises to 100°C and levels out at this temperature. After a while the temperature raises again and at this time the 100°C zone leaves the surface and moves towards the center. Outside the evaporation zone the temperature profile is very steep and the moisture content very low compared with the initial water content. The low water content in combination with the high temperature cause the Maillard reactions. In pure meat at lower temperatures the Maillard reaction does not occur normally (7). In minced meat products there are ingredients mixed with the meat that can accelerate the reaction and there are also some ingredients that can regulate the water holding capacity (WHC). Both of these properties may affect the frying operation and the property of the crust.

Different histochemical staining methods can be used to examine the chemical changes. Among other things it is known that reducing substances are formed in the Maillard reactions. There is a staining method for reducing substances which was used here in order to characterize the crust.

Materials and Methods

Recipe and oven design.

A recipe of known ingredients was made to follow the structural and the chemical reactions during frying. Together with the Meat Research Institute in Kävlinge, Sweden, a recipe according to table 1 was worked out. The following demands were fulfilled by the recipe.

- 1) It should have low weight losses
- 2) It should be easy to cut
- 3) It should give a brown coloured crust fried in a convection oven
- 4) It should not contain too many ingredients
- 5) Egg white proteins should be one ingredient
- 6) The recipe should behave similarly to one used in the industry.

Table 1. Ingredients of the minced meat recipe used.
(Percent of total)

Meat *	Water (extra)	Potato starch	Bread Crumbs	Egg white Powder	Spices	Total fat content (%)	Total water content (%)
75	15	2.5	4.5	1	2	11.3	66.3

* Mixed bovine and pork muscles.

The minced meat mixture was made into loaves of the dimensions 200 x 50 x 50 mm as this geometry is suitable for convection oven frying (8). A research convection oven was used and has been described in the literature (9).

Experimental Procedure.

1. Frying procedure

One minced meat loaf was frozen and used as a reference.

During the frying the loaves were placed in a teflon coated net cage to avoid deformation. Two different frying experiments were carried out; 1) until the temperature in the center reached 70°C and 2) for one hour. A temperature of 65-70 °C in the center of the loaf is considered a relevant end temperature for a cooked product since at this temperaturinterval patogenic micro-organisms are killed and proteins denatured. The air temperature was 225°C, the air velocity 5 m/s and the air was not humidified. Thin thermocouples of chromel alumel were placed in the loaf at different distances from the surface. The surface temperature was measured by an IR-sensing head as described earlier (9). After frying the loaves were frozen for microscopic analysis.

2. Preparing of tissue sections for microscopic studies

The loaves were cut in small cubes 10 x 10 x 10 mm and put into pots with fixing solution. For cutting these pieces into thin sections a microtome was used (type "Om E" C. Richert, Wien). The meat cubes were placed on the object stage and frozen with carbon dioxide under pressure, the thickness of the sections was 30-90 µm. Before staining the sections were put in a petri-dish

filled with water.

The sections were placed in a solution called the Fontana solution containing ammonical silver. The reaction between the reduced substances in the crust and the solution gives black spots of metallic silver as a result; a red colour was used for contrast-colouring. The coloured sections were placed on slides covered with coverslips for microscopic examination.

3. Microscopic studies and photographing

A research microscope (Jena. type Nf) with camera equipment was used to observe the structural changes. Photo slides where the enlargement was 20 times, were taken. Some photos of the microscopic slide were taken directly and this way the enlargement was 10 times. The reason for this was that the whole section could be seen on the photo. These photos were copied according to the Cibachrome - A print system.

Results and Discussion

Figures 1, 2 and 3 shows pieces from the minced meat loaf at different frying stages; raw, fried until 70°C in the center (30 minutes) and fried for one hour (enlargement 10 times).

Figure 4 shows the time / temperature relationship at different distances in the meat loaf fried until center reached 70°C and figure 5 shows the same relationship for the one fried for one hour. From these time / temperatures relationships figure 6 was made. This shows the movement of the evaporation zone as a function of time and thus the growth of the crust. From linear regression of the time depth points, the following equation was derived

$$y = - 27 \cdot 10^{-2} + 0.12 \cdot 10^{-2} x$$

where y is the depth of the crust in mm and x is the time in seconds. After 30 minutes the crust is 1.9 mm and after 60 minutes 4 mm. Photographs 2 and 3 show a dark zone which is the part with reducing substances. Measuring this zone on the photo gives 1.5-2 mm after 30 minutes and 3.5-4 mm after 60 minutes.

These two results are in good agreement, which means that the histochemical staining method could be used for calculating the dept of the crust. As almost the whole crust was coloured black this might also mean that Maillard reactions or a similar one take place in the crust, but not in the inner parts of the loaf.

From the photos it can also be seen that it seems as if: 1) the crust is more porous than the inner parts, though the outer thin layer is rather tight and 2) the structure of the inner parts changed with frying. The raw piece had a few not very large pores but the fried ones had many large and small pores.

When trying to calculate the structural changes and to get the porosity of the product one has to bear in mind that most of the smaller white spots in the inner parts might be fat and not pores. This should be an object for further investigation.

Apart from what had happened in the crust during frying the following was seen. The different ingredients and their macroscopic changes could be recognized. The large red spots are muscles and the large white spots looking like a net are fat.

Many of the big nets of fat seem to disappear after frying and small fat spheres are spread on the sample of the product. As it is difficult to distinguish between fat and pores, a staining procedure for fat should be done. The bread crumbs can clearly be seen as dark brown spots on the raw piece of meat. They have faded a little on the piece of meat that has been fried for 30 minutes. This is probably due to absorption of water.

A preliminary investigation has been carried out to follow the potato starch corns in the recipe and the objects were photographed in polarized light. From this it seems as if the starch has hydrolysed except in some parts during frying. On a thin layer of the surface, corns remained intact lying like a string of pearls. Probably this layer has been dried and the temperature raised so quickly that not enough water was present to hydrolyse the starch.

This paper has described a method where changes, chemical and physical, could be followed during the frying of minced products. Further and deeper investigations have to be made to refine the analysis so as to gain more information.

Acknowledgements.

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Figure legends.

Figure 1. Raw minced meat. Enlargement 10 x

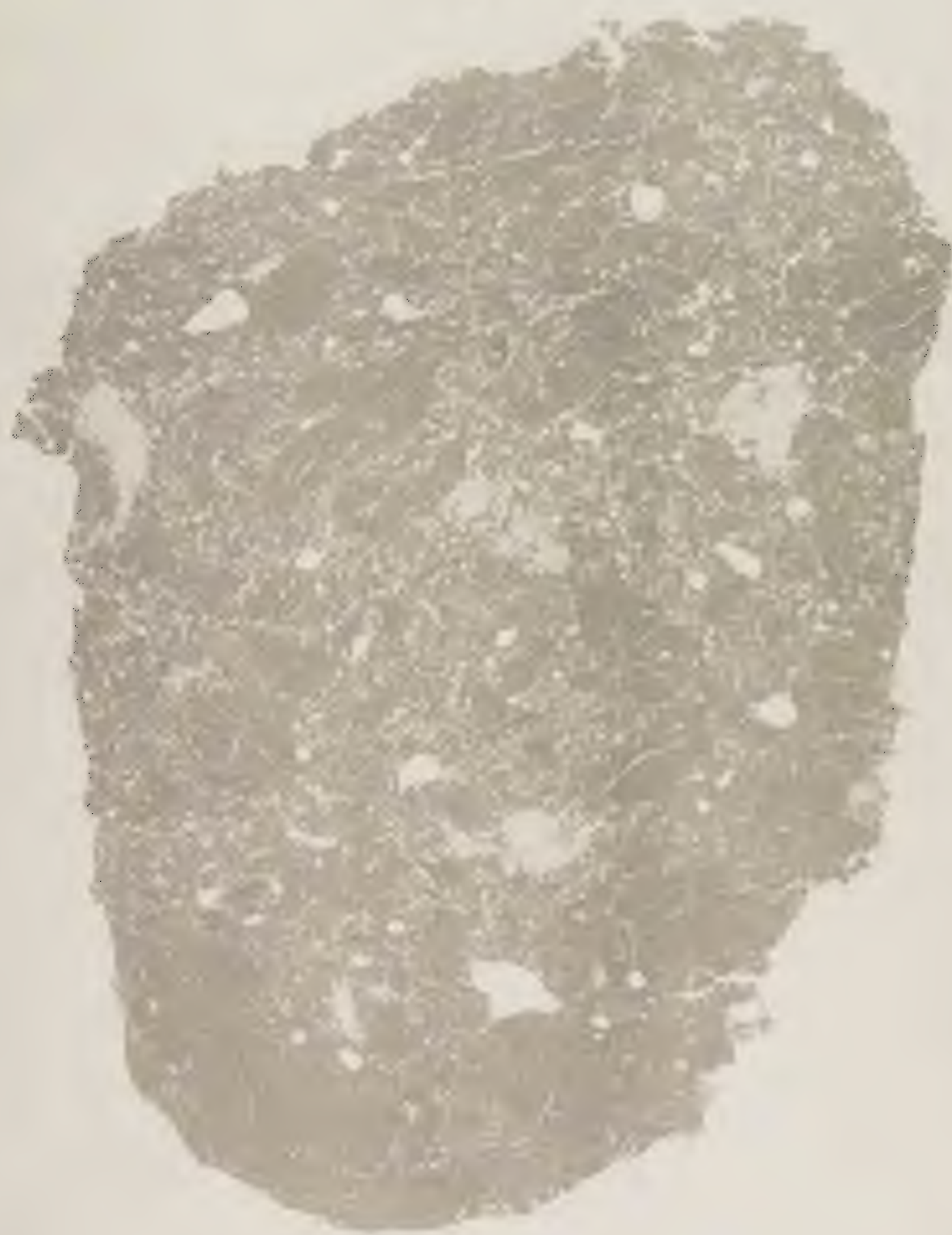
Figure 2. Minced meat fried until center reached 70°C
(total 30 minutes), enlargement 10 x

Figure 3. Minced meat fried for 60 minutes. Enlargement 10 x

Figure 4. Temperature in the product and on the surface as a
function of time (fried until the center reached
70°C).

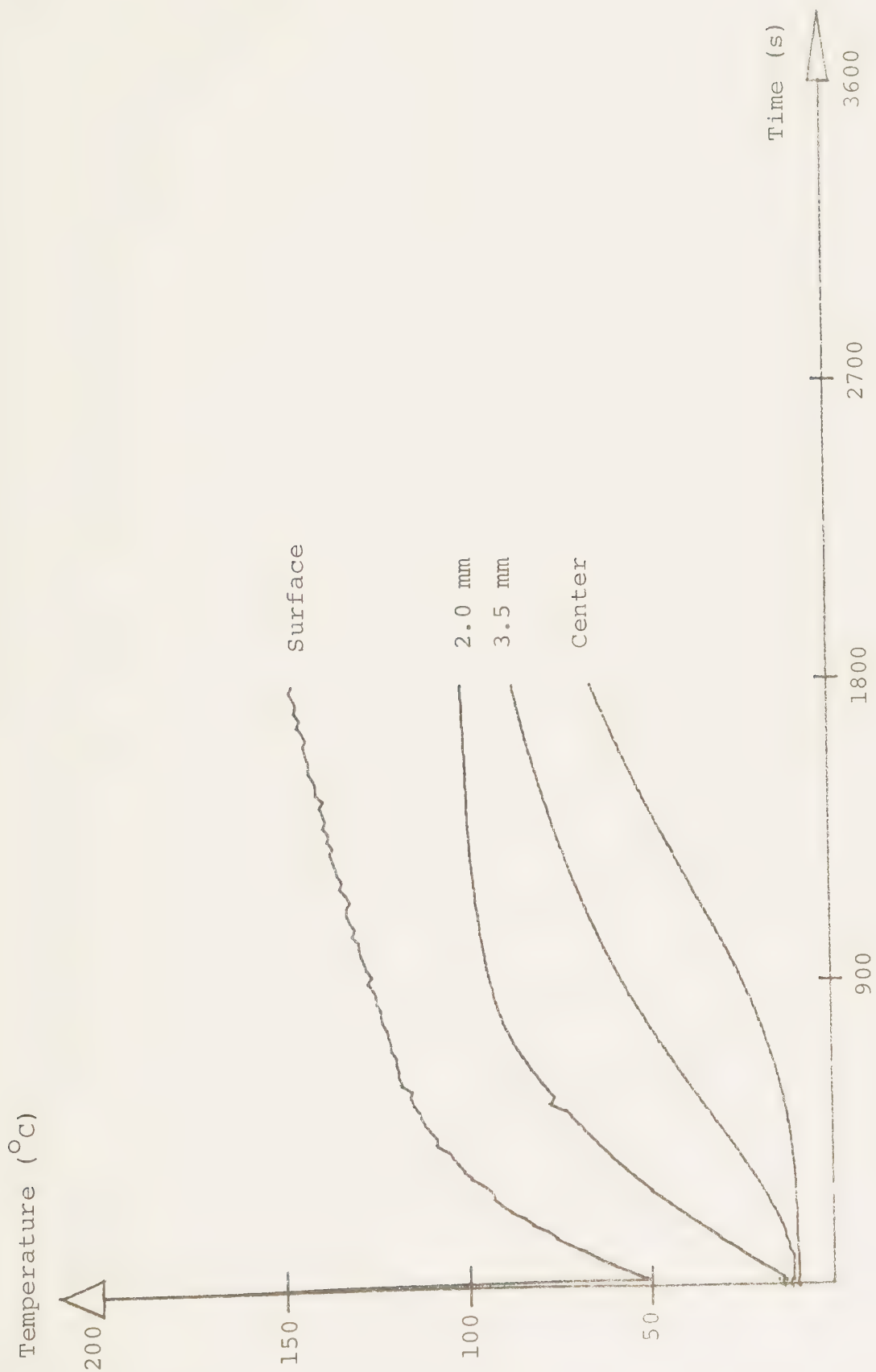
Figure 5. Temperature in the product and on the surface as a
function of time (fried for 60 minutes).

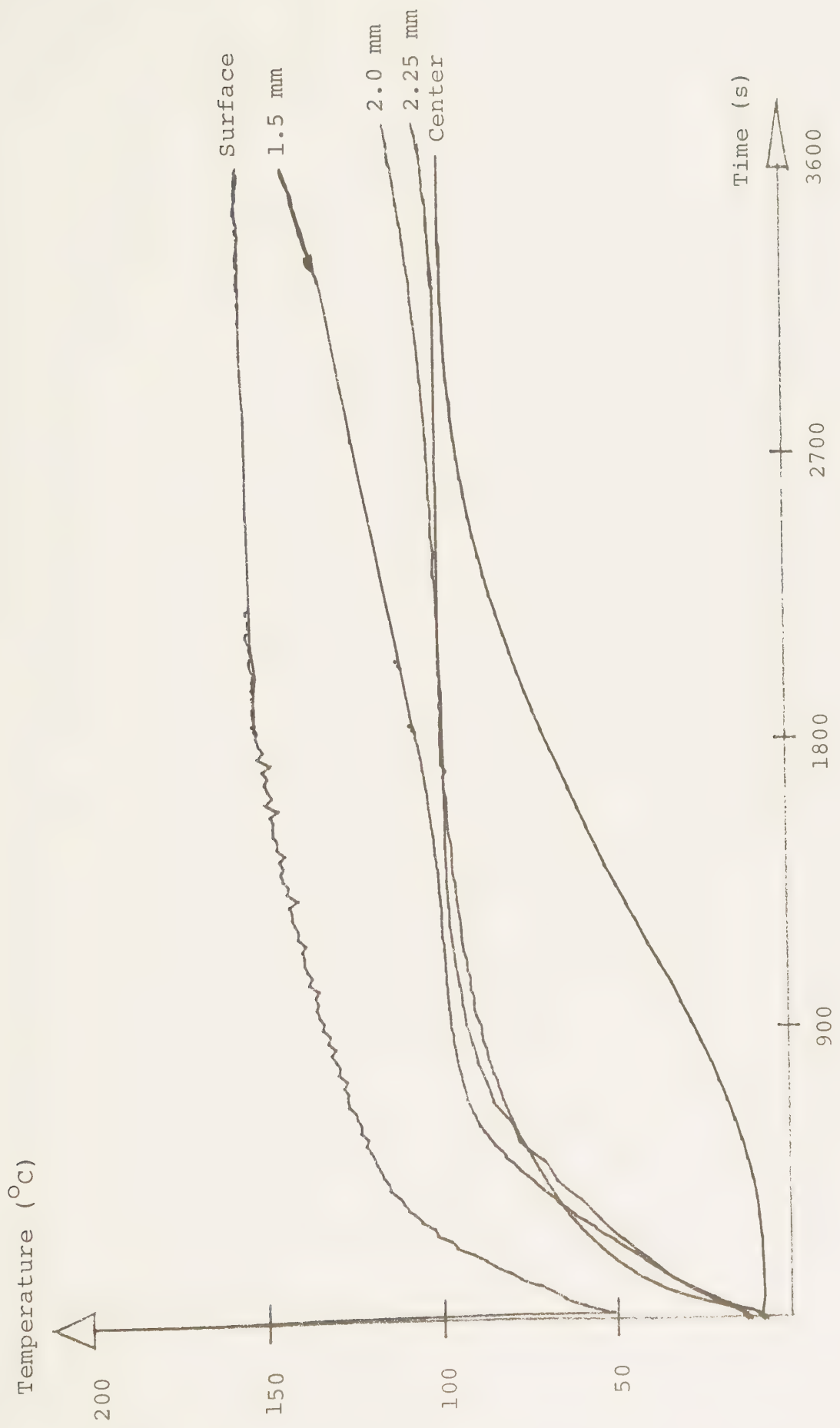
Figure 6. Crust depth as a function of time.











Depth (mm)

